

RECENT RESULTS OF DARK SECTOR SEARCHES WITH THE *BABAR* EXPERIMENT

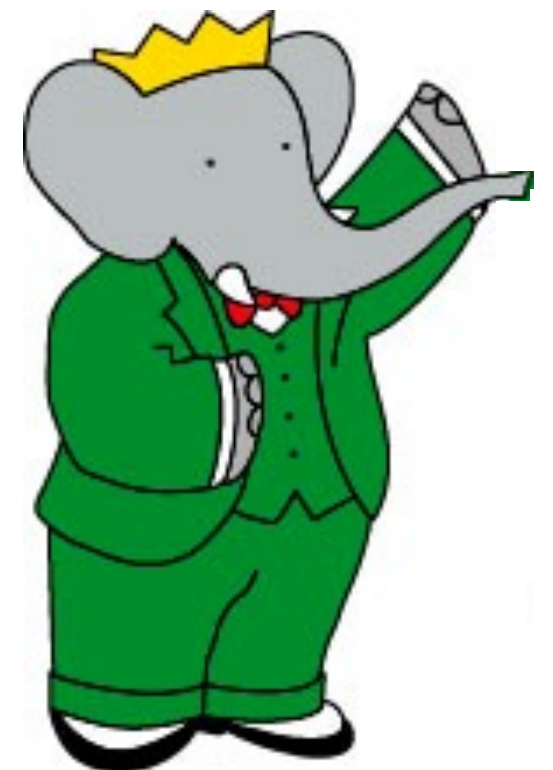
Brian Shuve

on behalf of the BABAR Collaboration

**HARVEY
MUDD
COLLEGE**

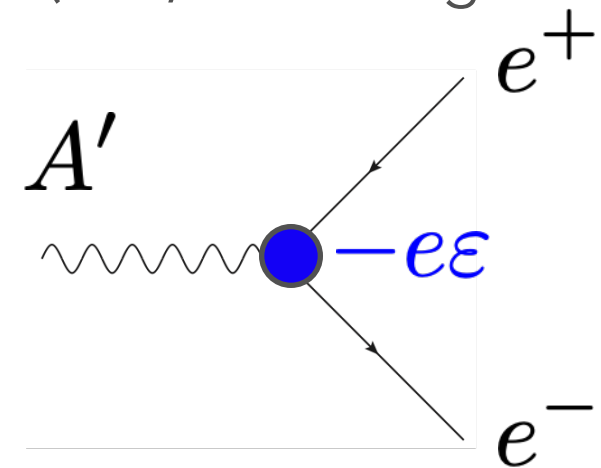
Opening New Windows to the
Universe

2021 Brookhaven Forum
November 3, 2021



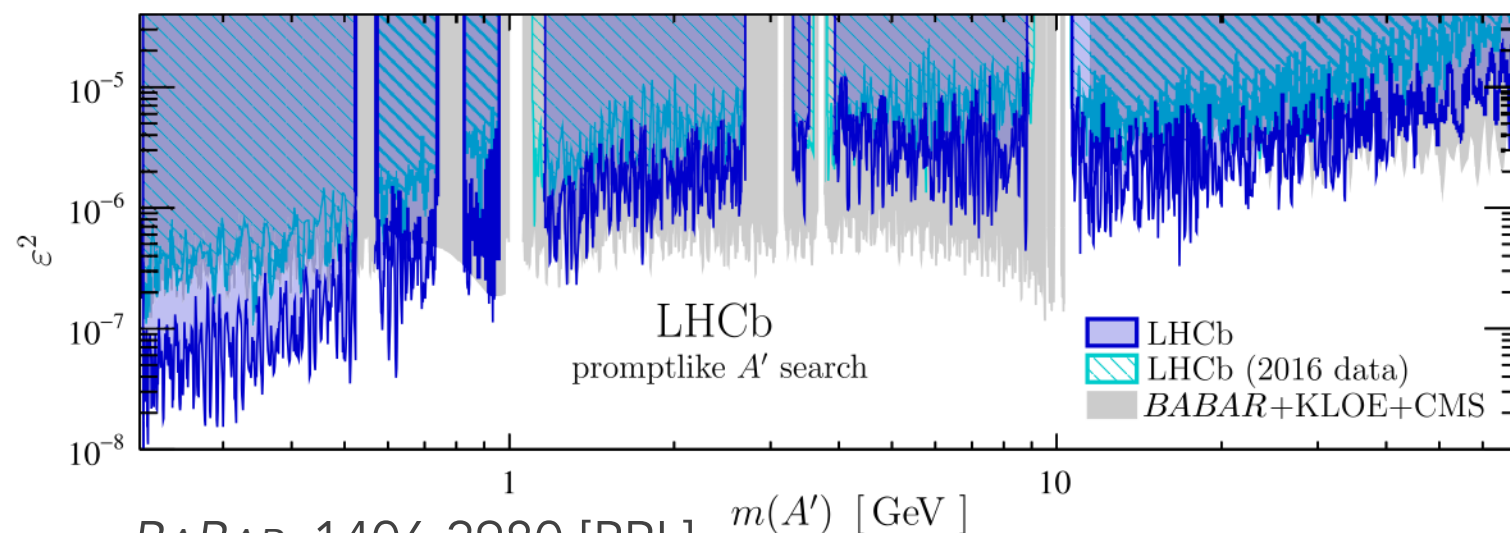
HIDDEN SECTOR DM

- For thermal dark matter masses below a few GeV, a low-mass mediator is needed for observed abundance (Lee, Weinberg 1977 [PRL])
- Many searches focus on minimal, predictive “portals”, such as a dark photon (A')



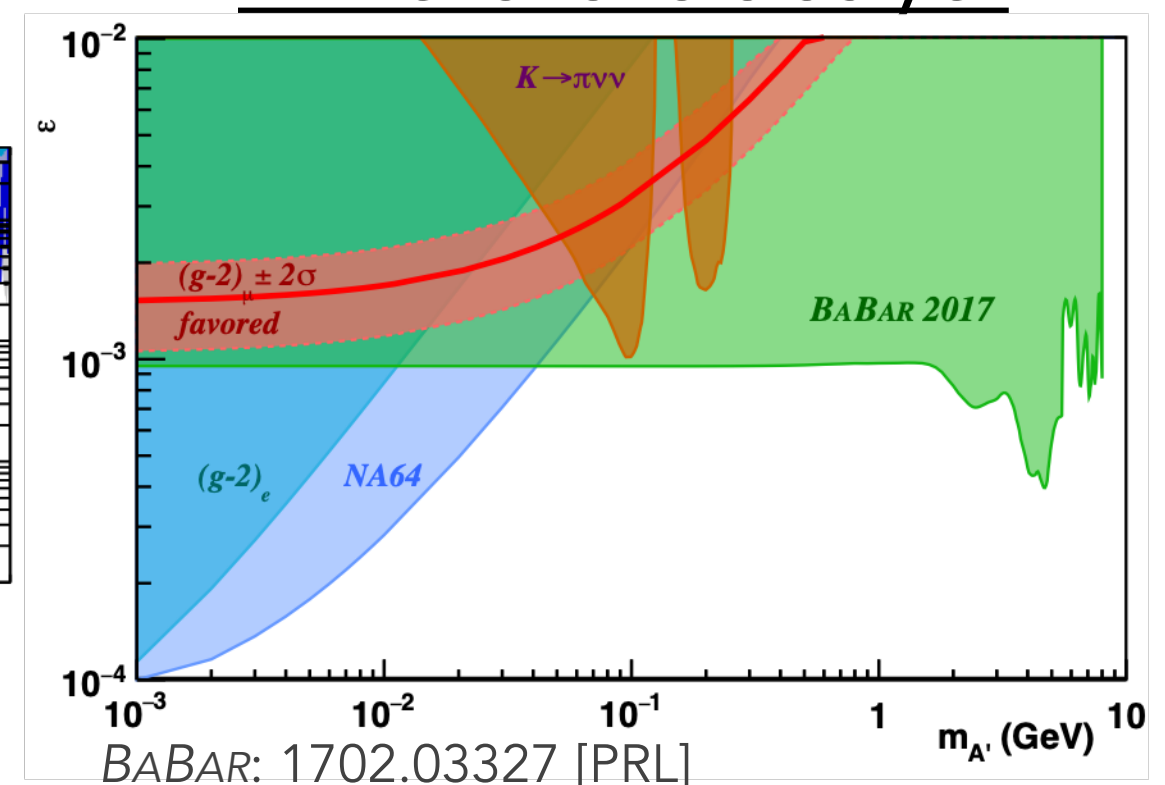
visible decays: $A' \rightarrow \ell^+ \ell^-$

invisible decays:



BABAR: 1406.2980 [PRL]

LHCb: 1910.06926 [PRL]

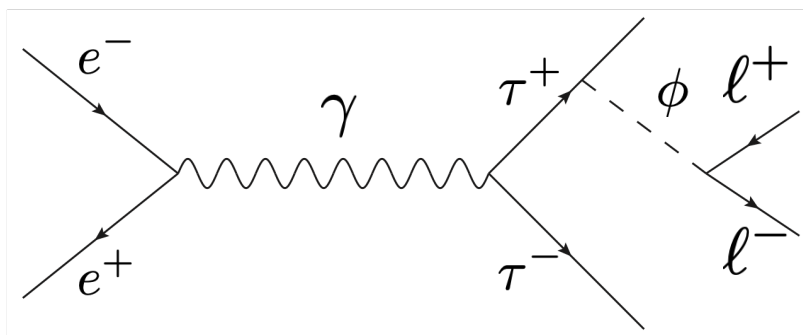


BABAR: 1702.03327 [PRL]

BEYOND MINIMAL PORTALS

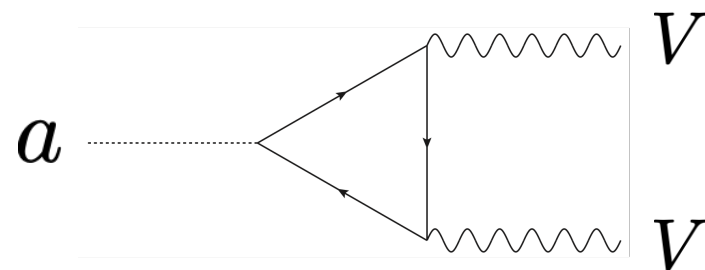
- Hidden sector dynamics can predict signals that differ from canonical portal searches, require new strategies

leptophilic forces



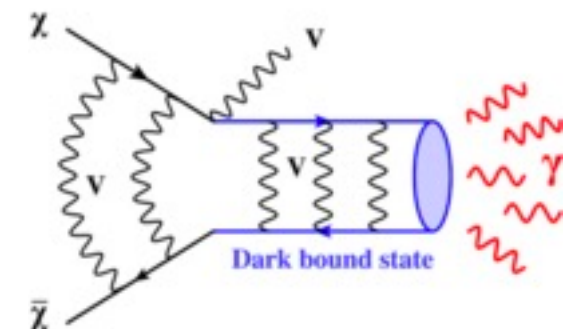
BABAR, 1606.03501 [PRD]
BABAR, 2005.01885 [PRL]

axionlike particles



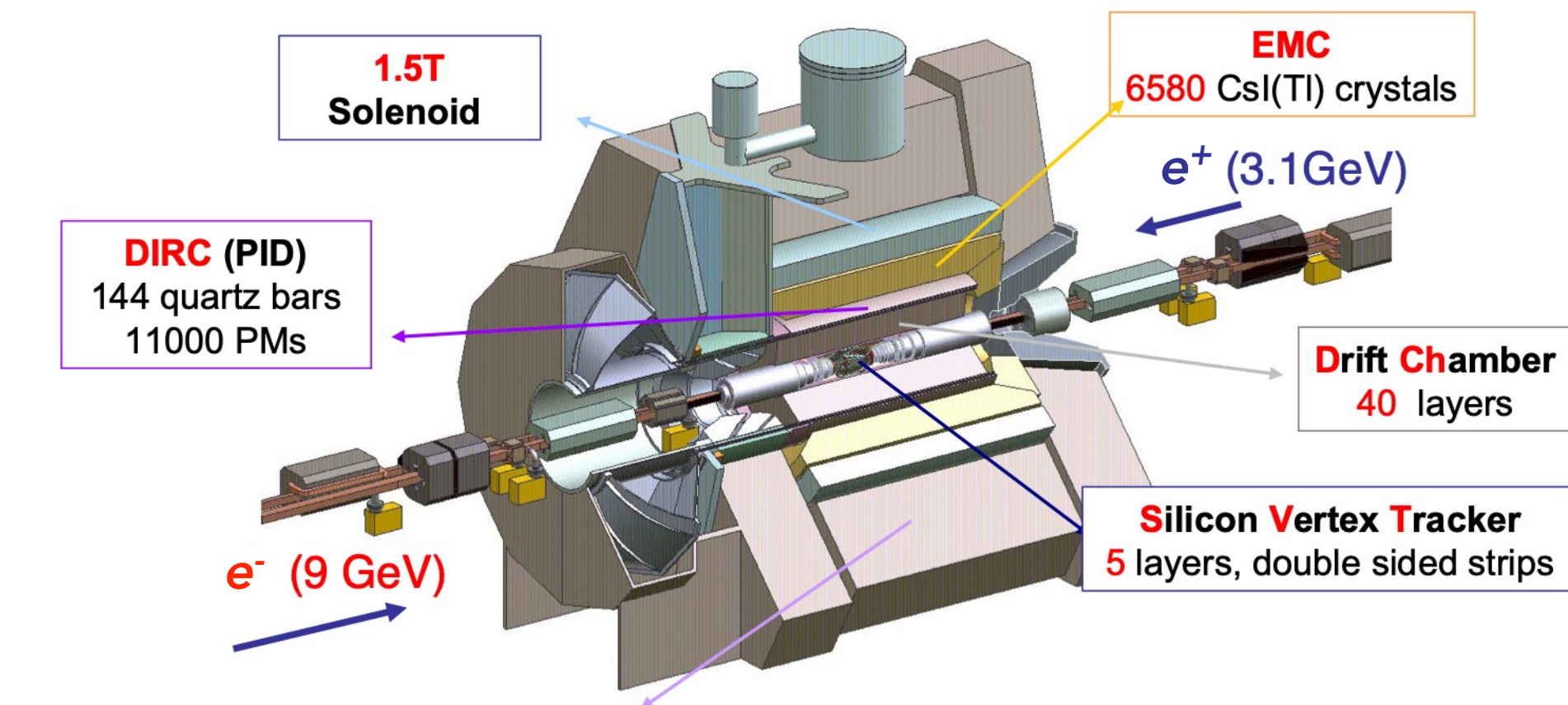
BABAR, preliminary
3

DM bound states

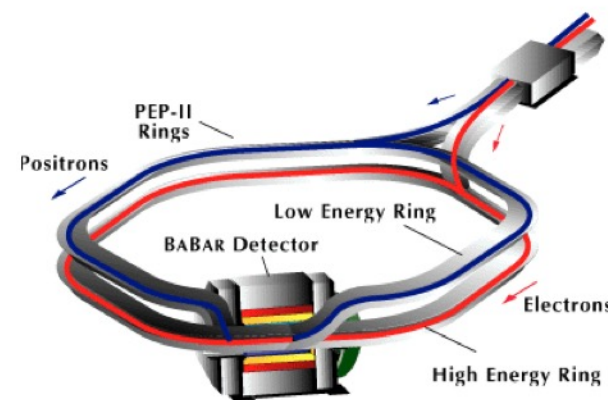


BABAR, 2106.08529

BABAR EXPERIMENT



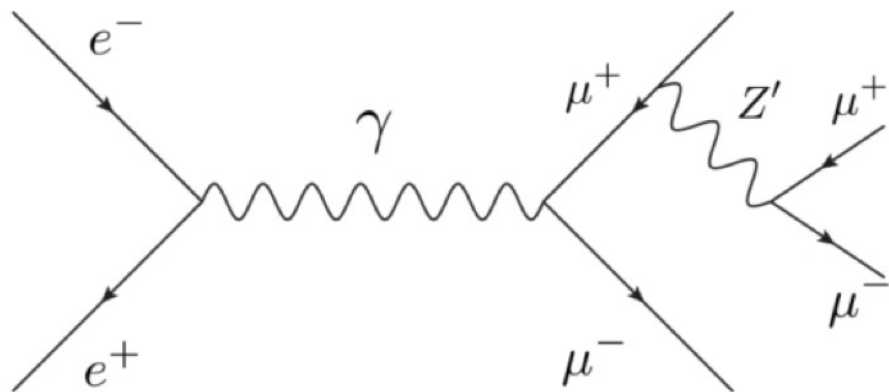
1999-2008



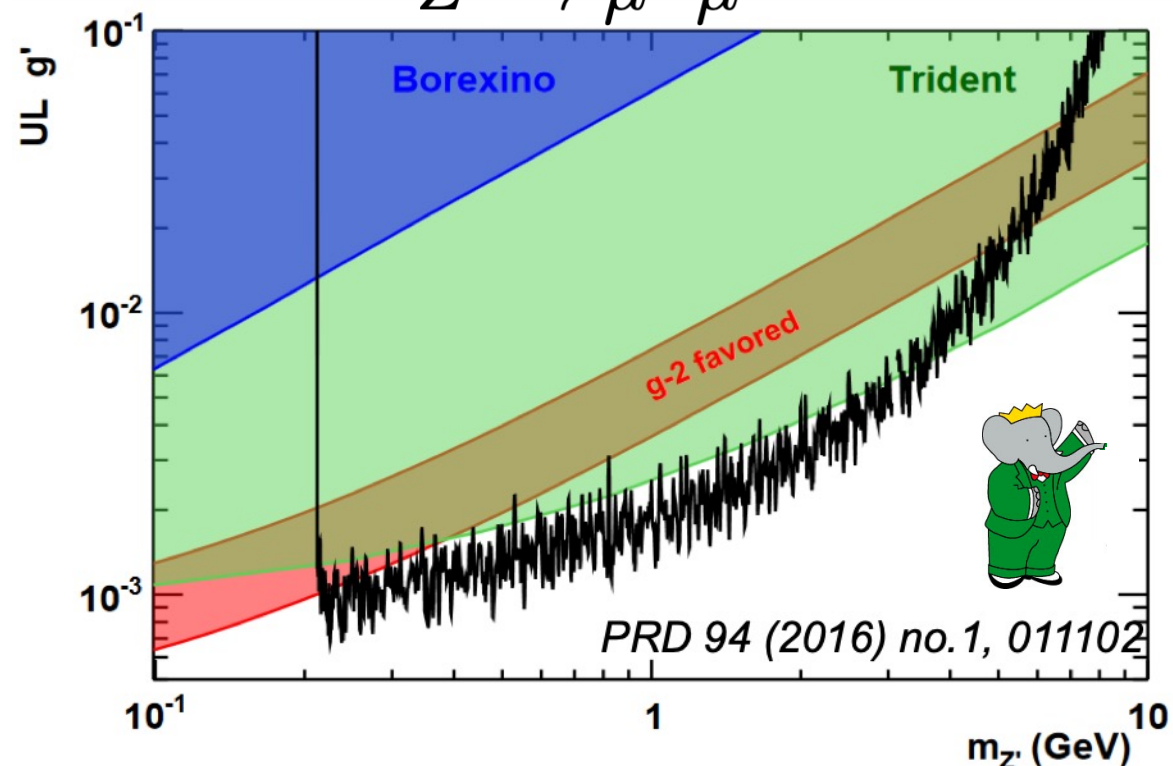
- 432/fb $\Upsilon(4S)$ on peak
- 53/fb non-resonant (off peak)
- smaller samples at $\Upsilon(2S)/\Upsilon(3S)$

LEPTOPHILIC FORCES

- Mediator couples predominantly to muons or taus, can explain muon $g-2$ while satisfying other constraints

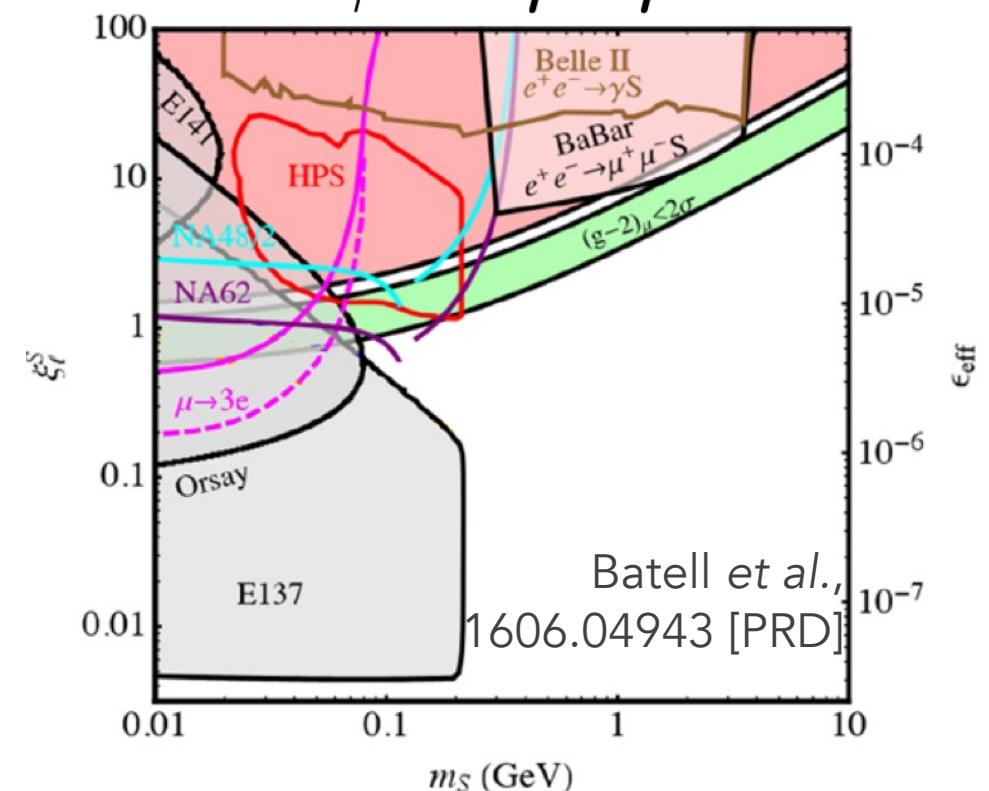


$$Z' \rightarrow \mu^+ \mu^-$$



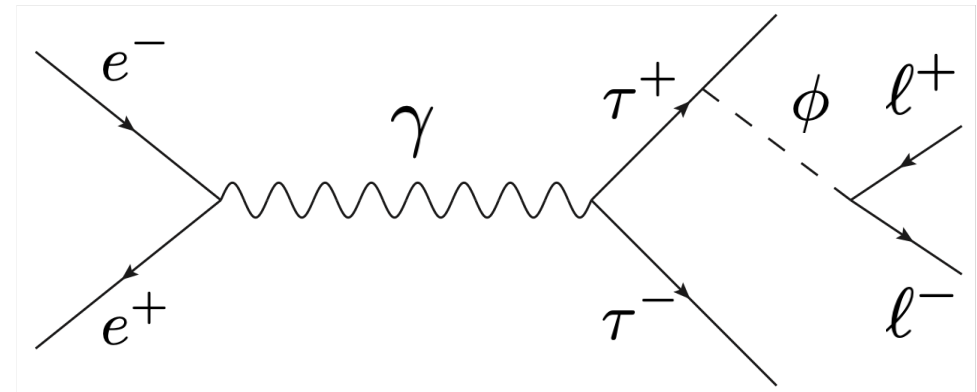
- Search for dilepton resonance in association with two muons
- BABAR* muonic force searches constrains $m_{Z'} > 2m_\mu$

$$\phi \rightarrow \mu^+ \mu^-$$



LEPTOPHILIC SCALAR

- In many scalar models, the scalar has **mass-proportional coupling**, so more sensitivity can be obtained through production with taus
- Mediator mostly decays to heaviest accessible lepton
 - Prompt decays to muons for $m_\phi > 2m_\mu$
 - Displaced decays to electrons for $m_\phi < 2m_\mu$
- Consider all single-pronged tau decays, trained BDTs for each final state & lifetime to increase signal purity (event shape, vertex information, kinematic observables)



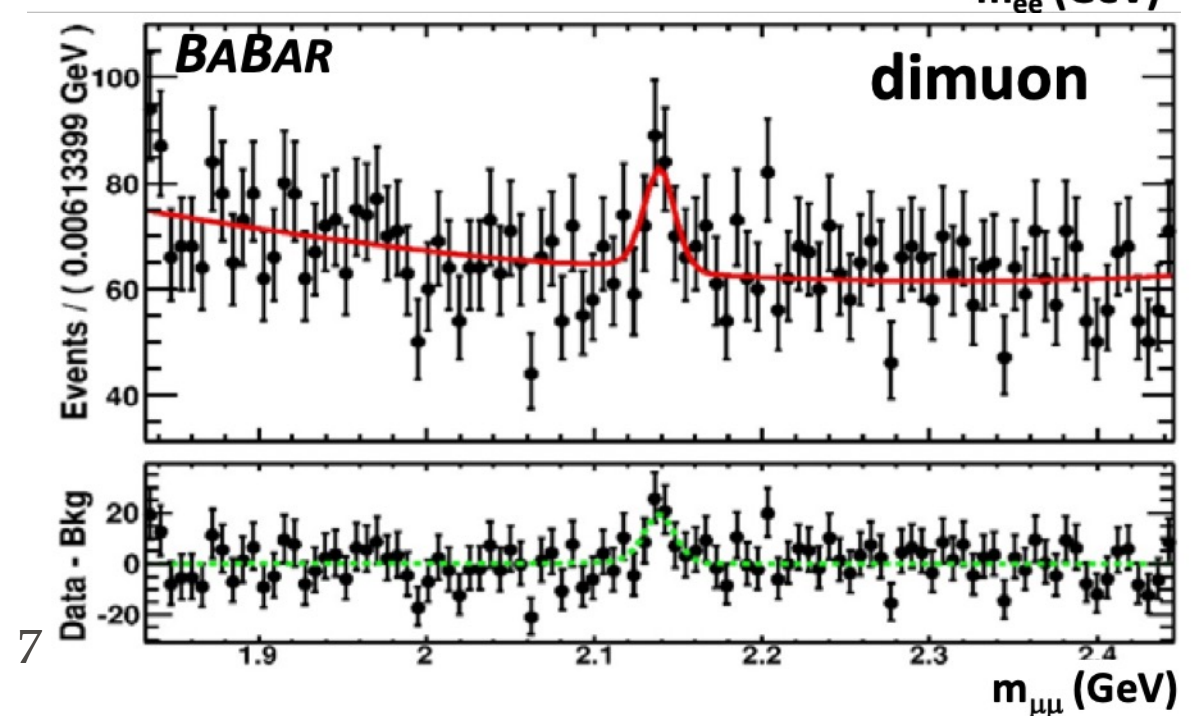
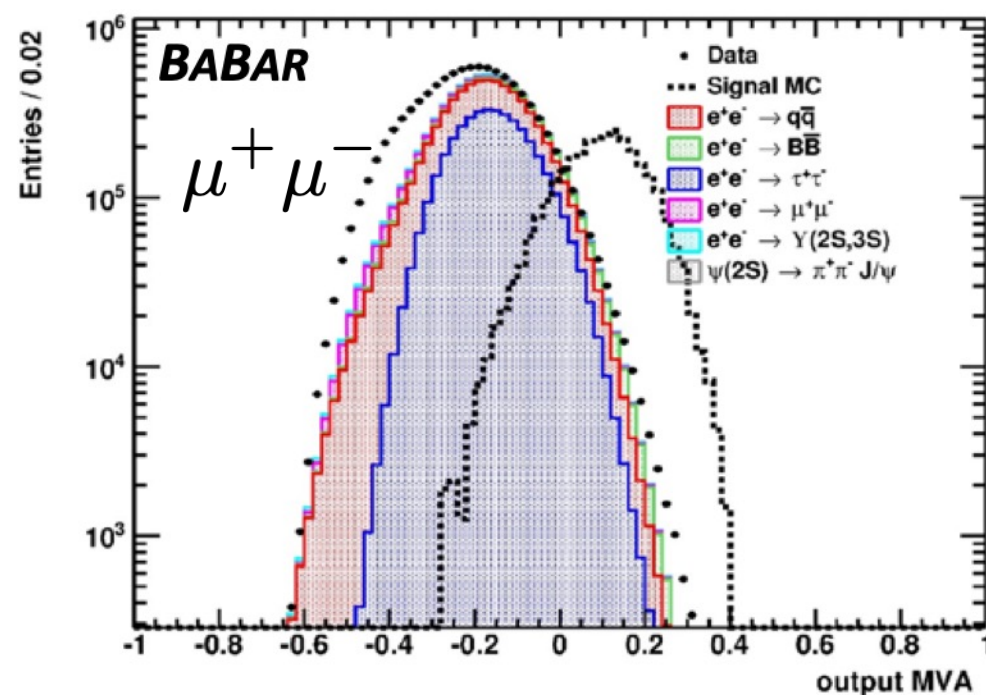
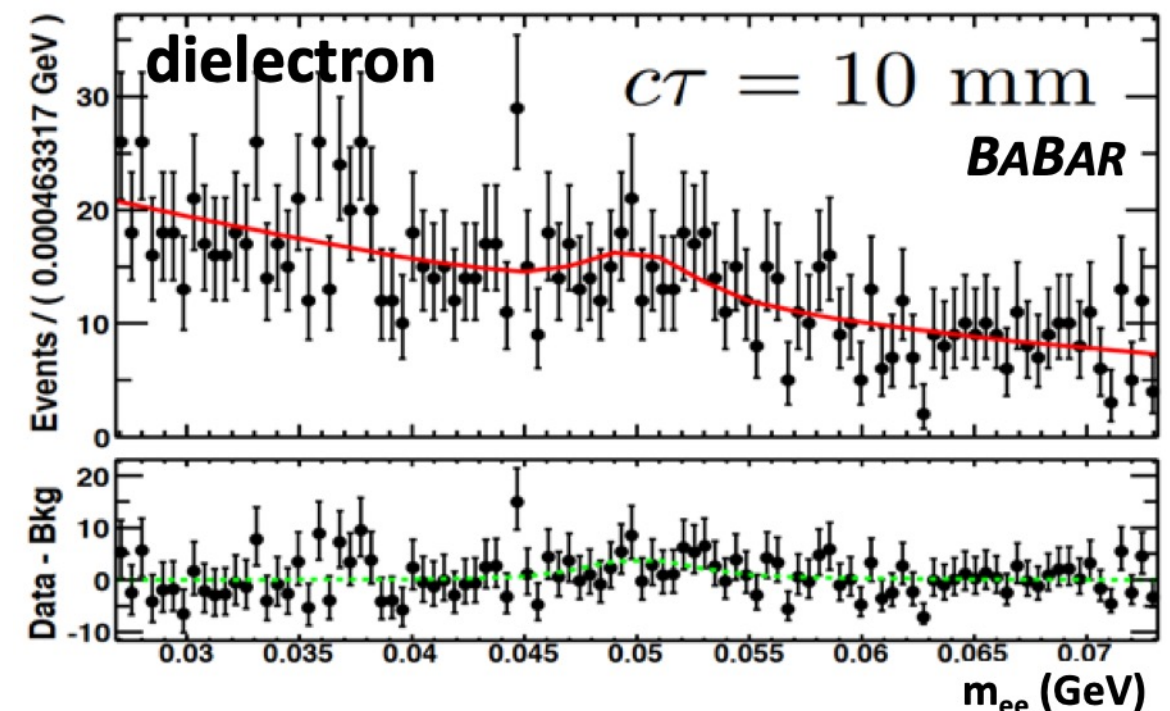
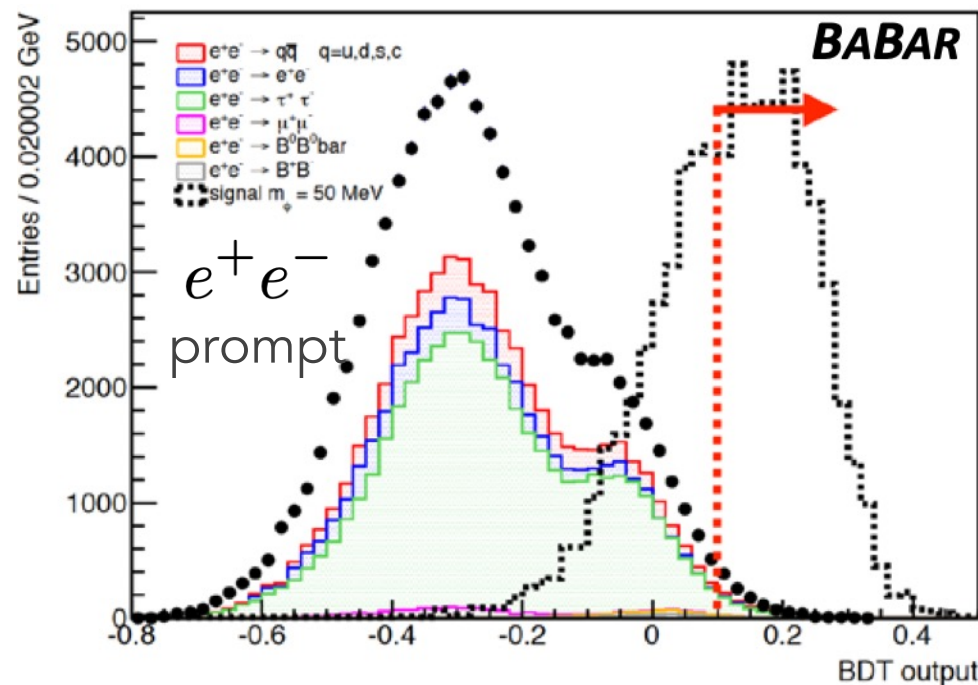
$$g_\ell \propto m_\ell/v$$

Batell et al., 1606.04943 [PRD]
see also Chen et al., 1511.04715 [PRD]

BABAR, 2005.01885 [PRL]

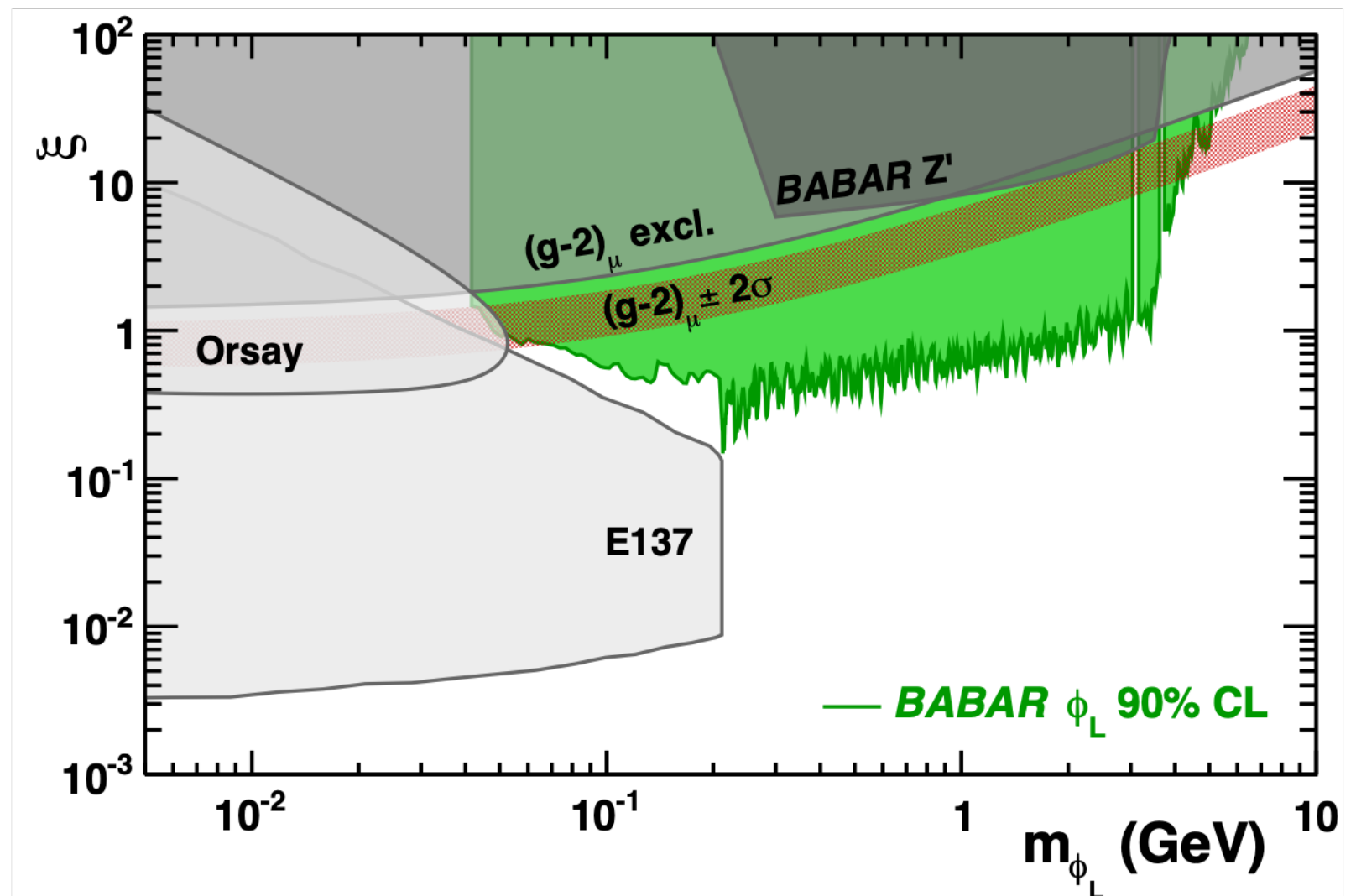
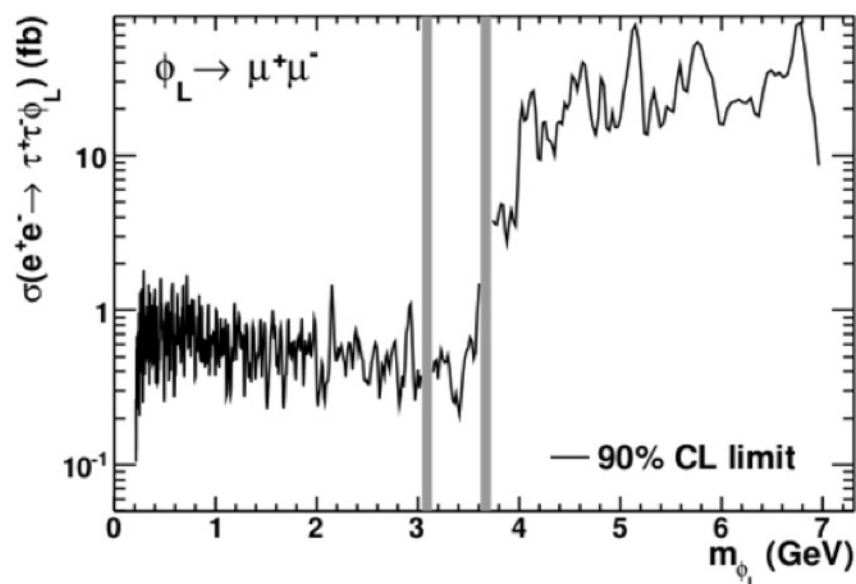
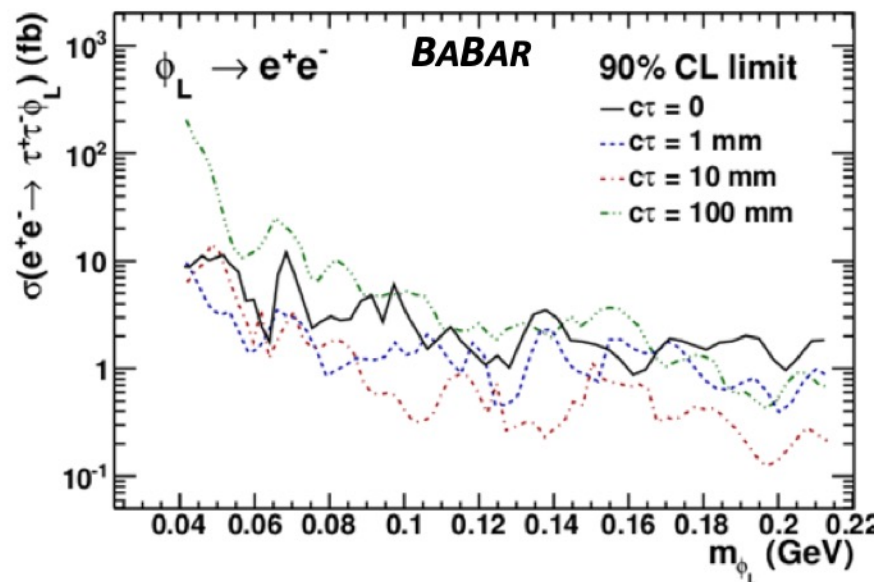
LEPTOPHILIC SCALAR

- Use MC-independent model for background, look for **narrow** peak



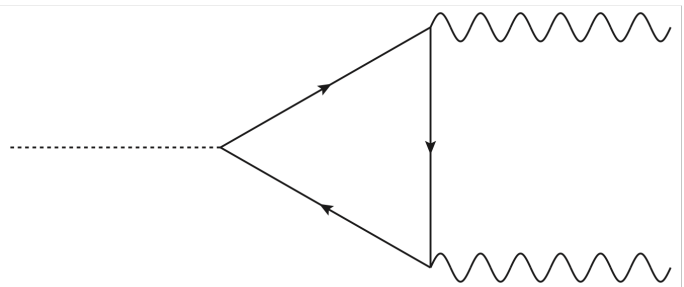
LEPTOPHILIC SCALAR

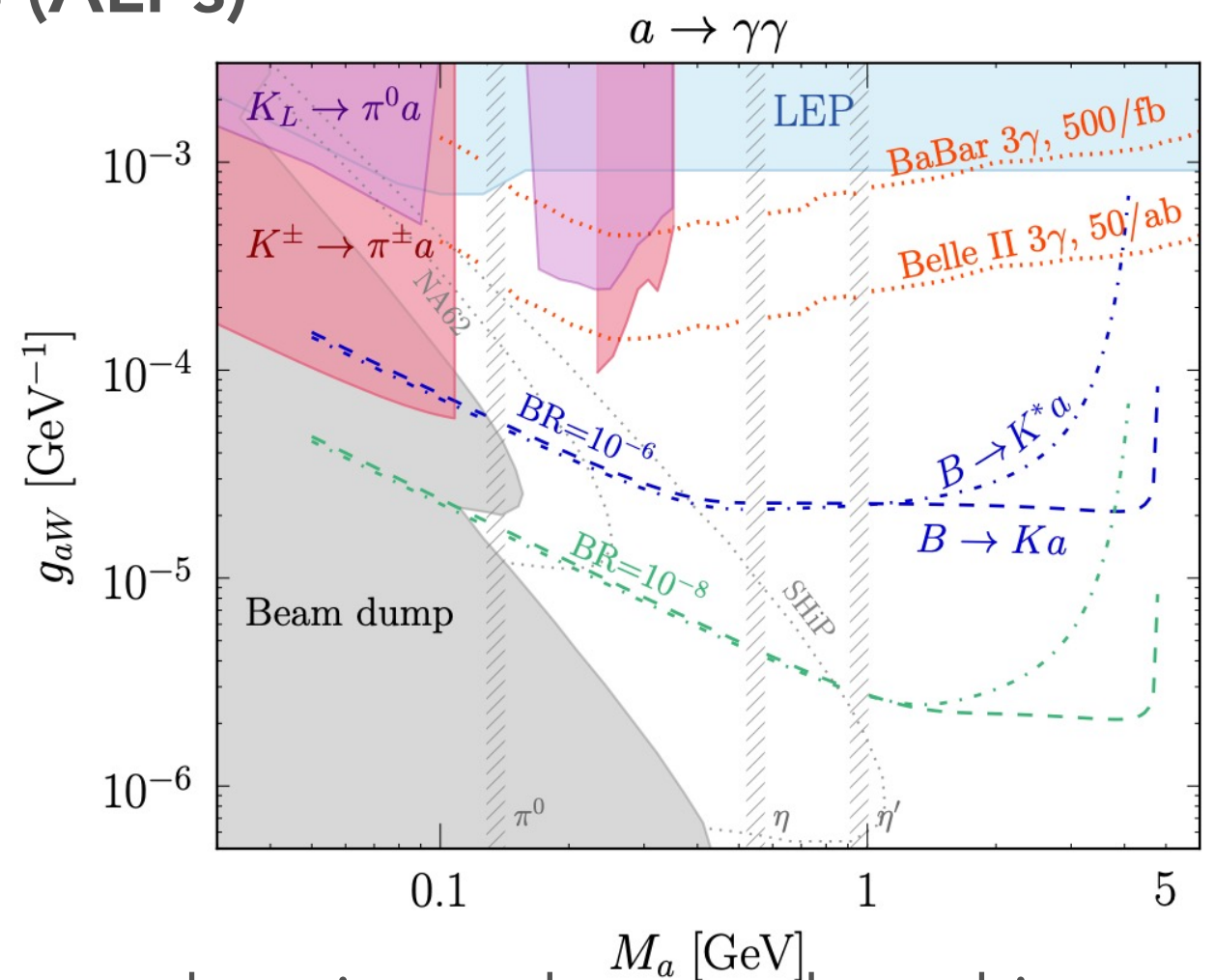
- In the absence of significant signal, we set model-independent 90% CL cross section limits, as well as limits on the leptophilic model coupling



AXIONLIKE PARTICLES

- Another major gap exists when mediators couple predominantly to gauge bosons: **axionlike particles (ALPs)**

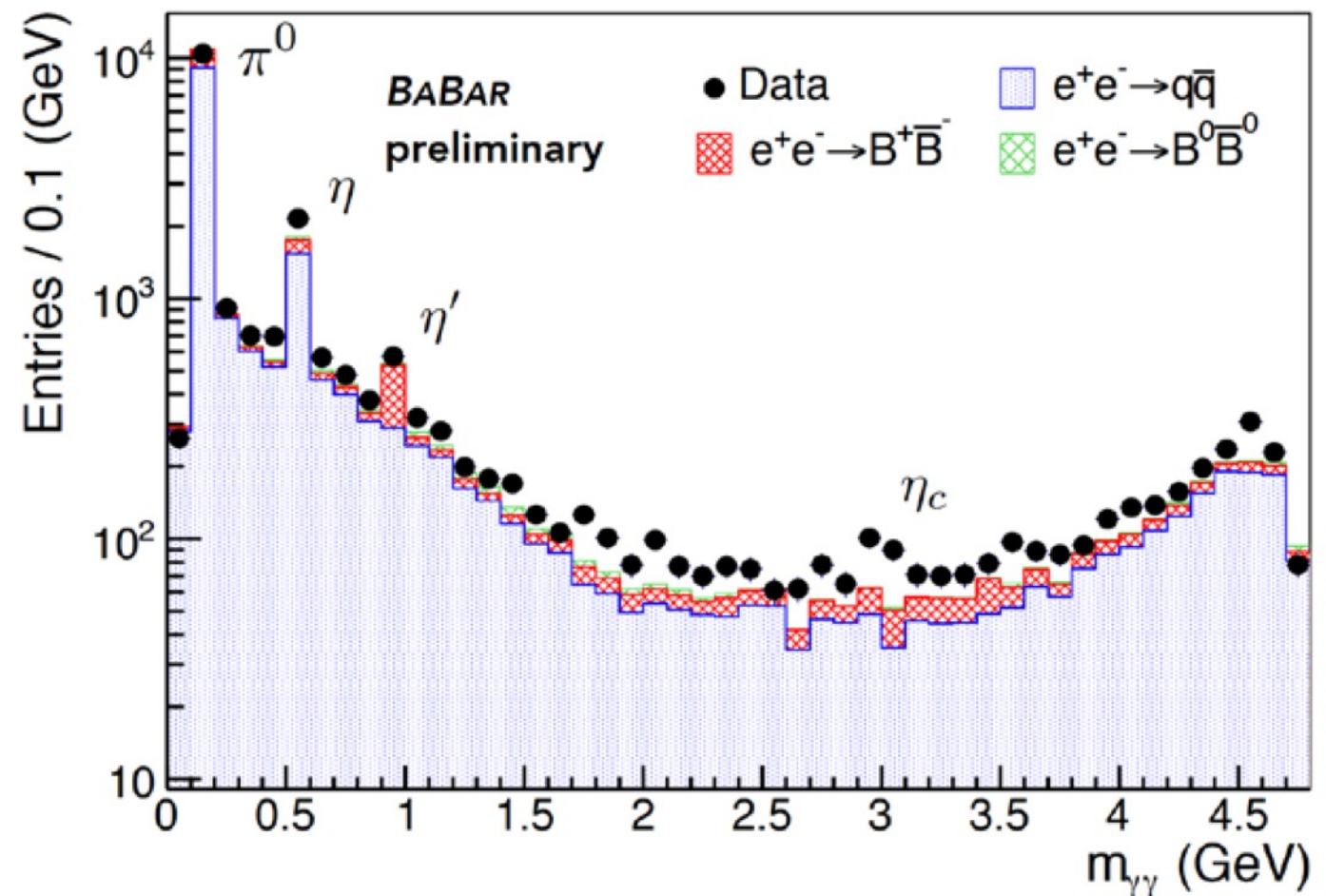
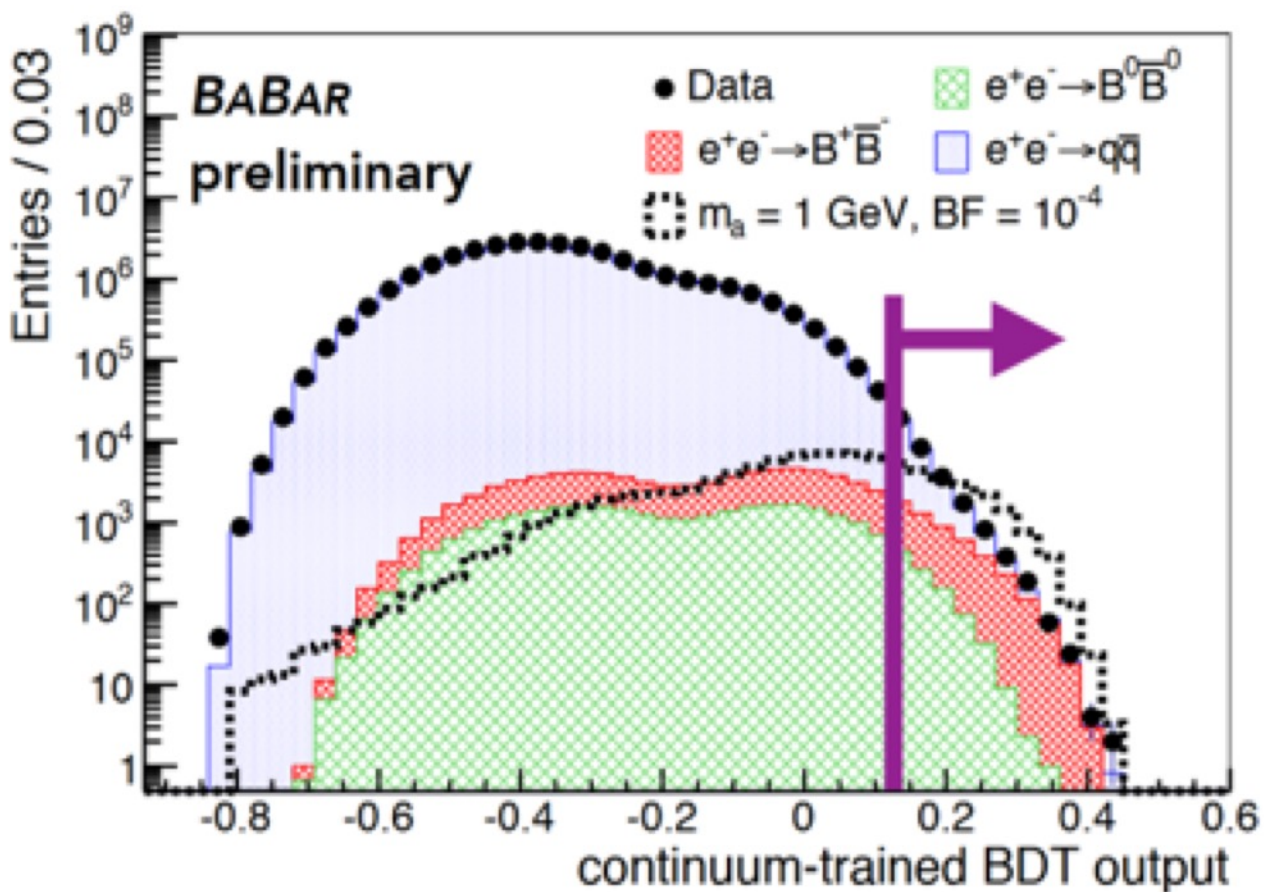
$$\mathcal{L} = -\frac{g_{aV}}{4} a V_{\mu\nu} \tilde{V}^{\mu\nu}$$




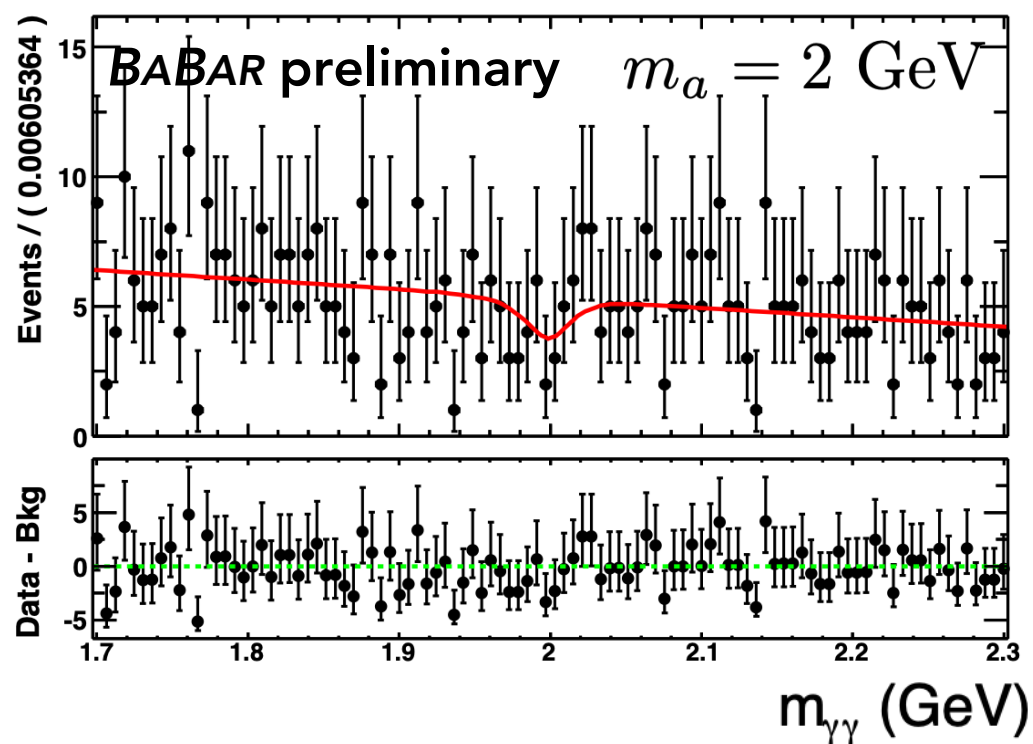
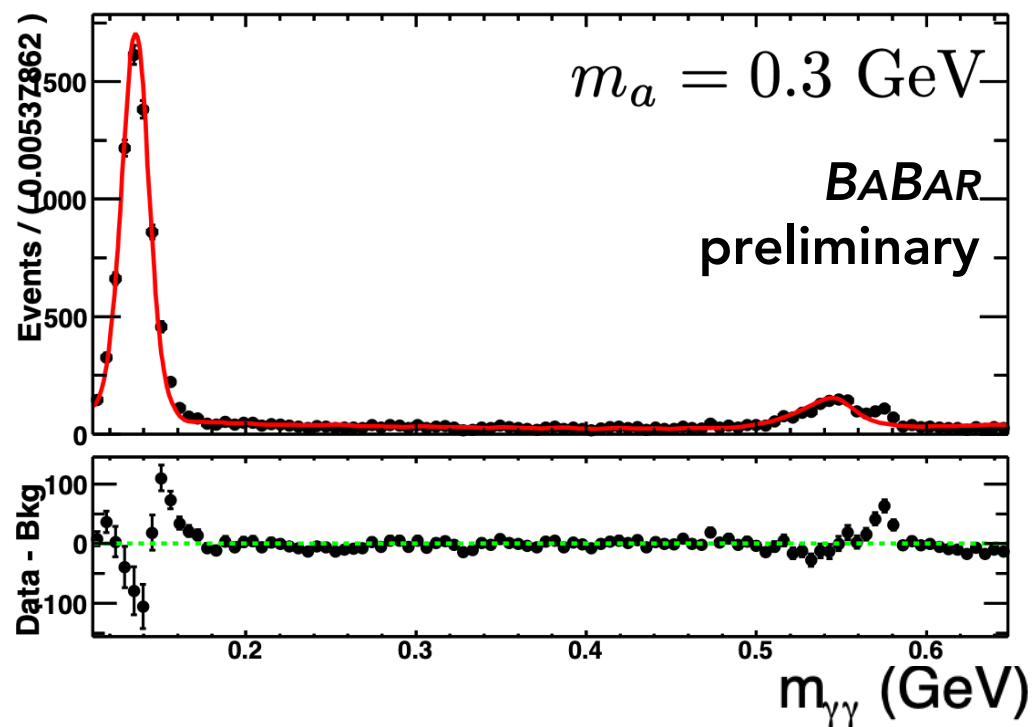
- If ALP couples to SU(2) gauge bosons, then it can be produced in rare B meson decays: $B^\pm \rightarrow K^\pm a$, $a \rightarrow \gamma\gamma$
- This mode can give best sensitivity to the model!

AXIONLIKE PARTICLES

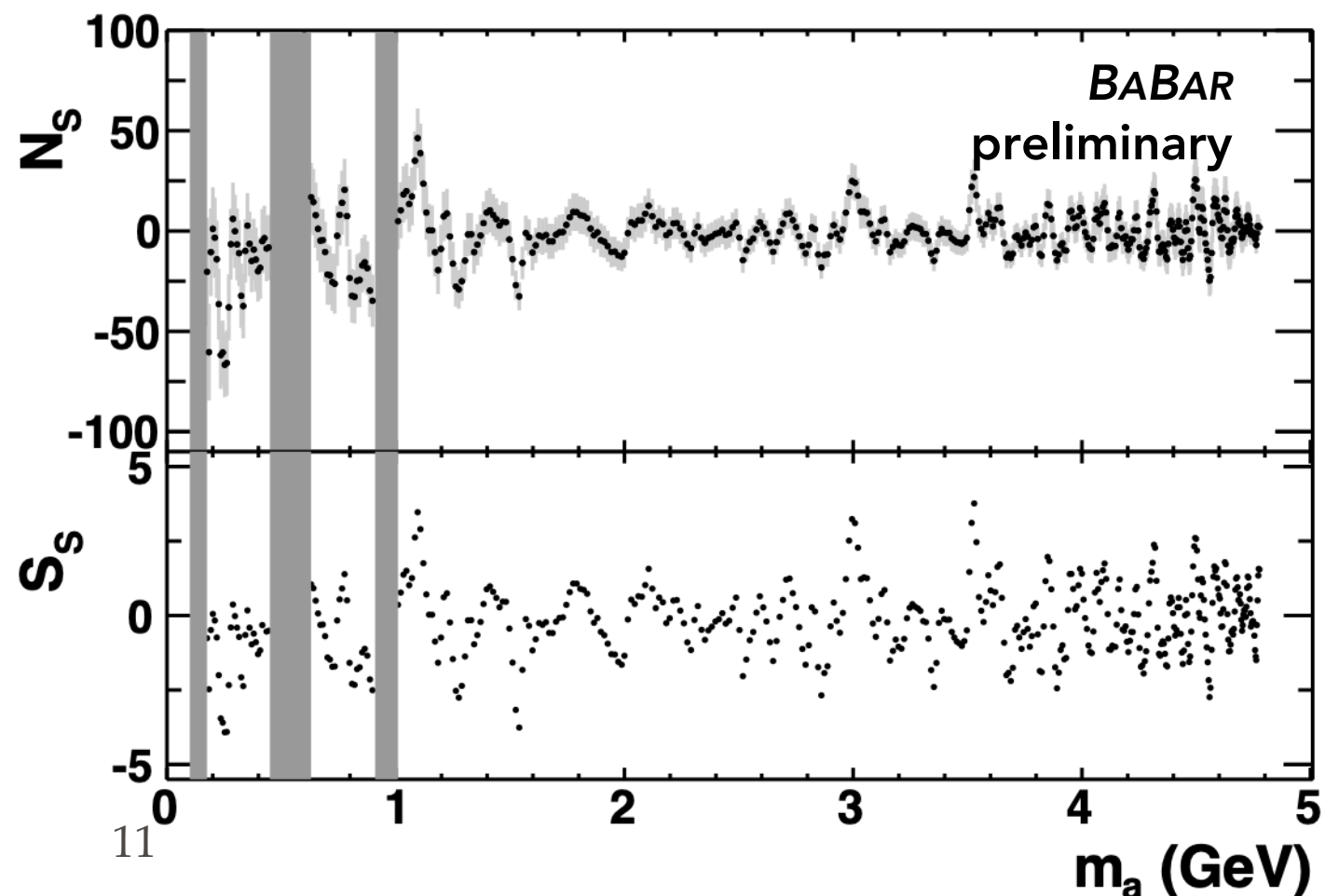
- Reconstruct $B^\pm \rightarrow K^\pm a$, $a \rightarrow \gamma\gamma$ candidates (with a kinematic fit to improve resolution), look for narrow peak (~ 8 -30 MeV) in diphoton mass
- Train BDTs to reject dominant backgrounds (light-quark + B-meson)



AXIONLIKE PARTICLES

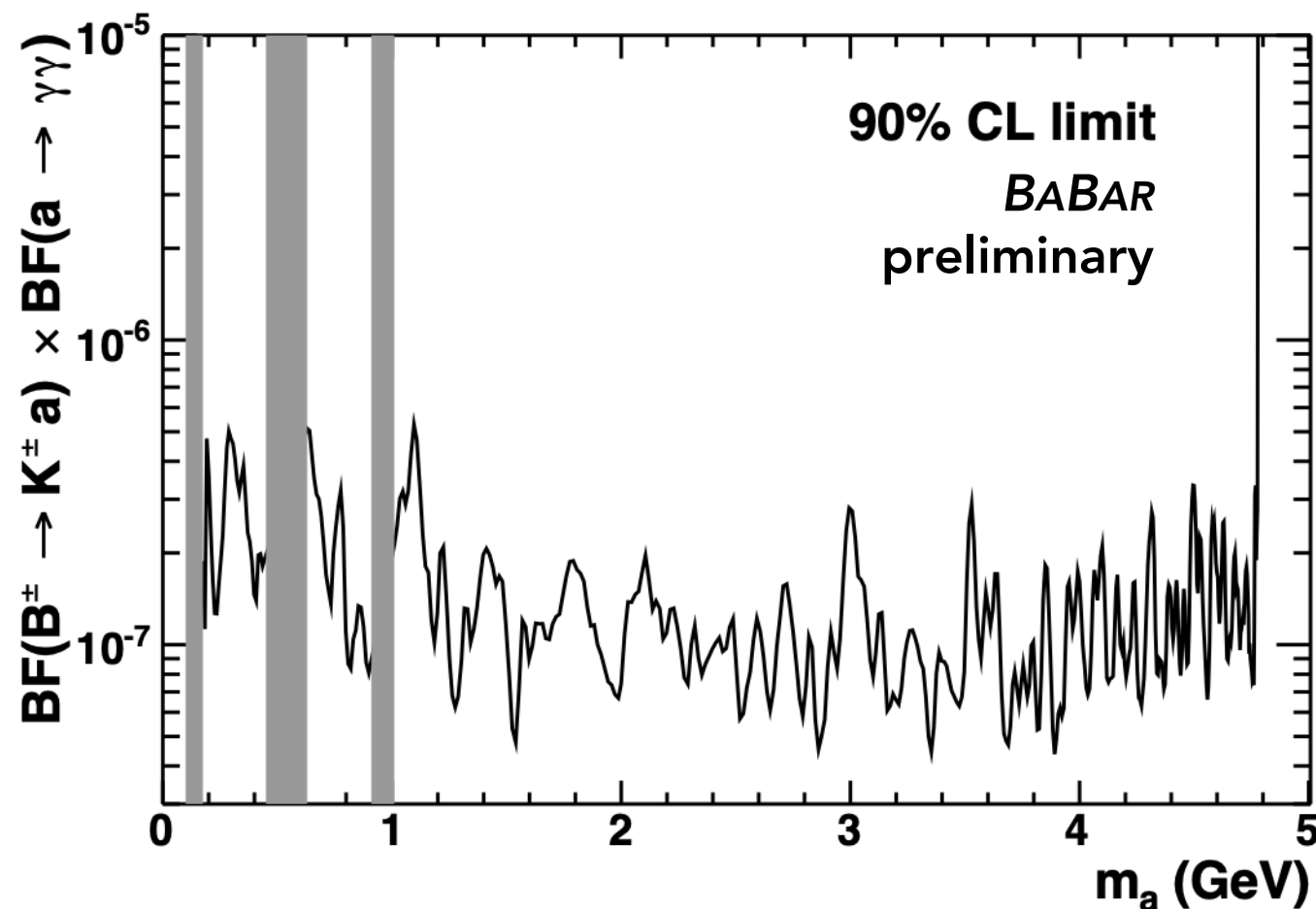


- (left) sample fits
- (right below) signal yield and local significance
- most significant excess $< 1\sigma$ after including trial factors

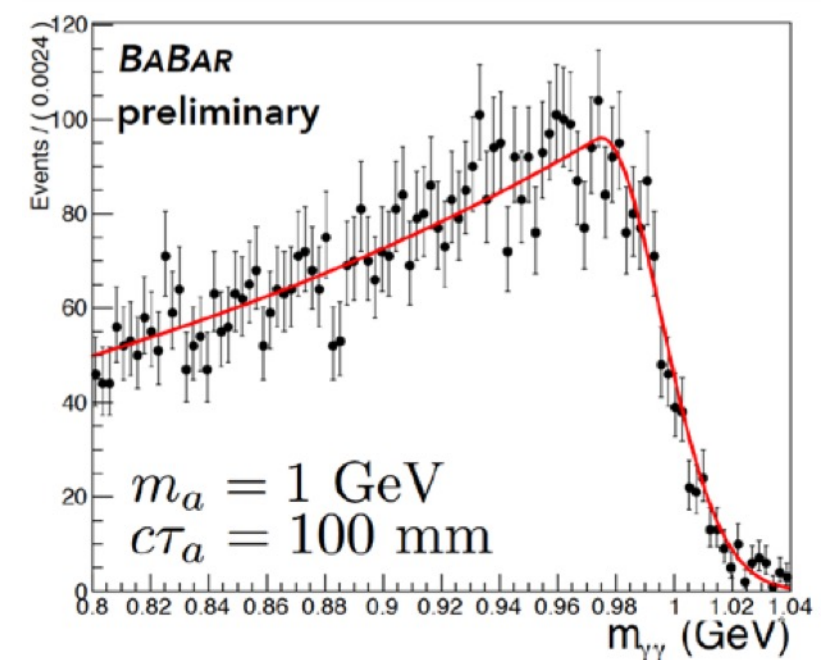


AXIONLIKE PARTICLES

- In the absence of significant signal, Bayesian 90% CL upper limits are derived on $BF(B^\pm \rightarrow K^\pm a, a \rightarrow \gamma\gamma)$ assuming prompt decays

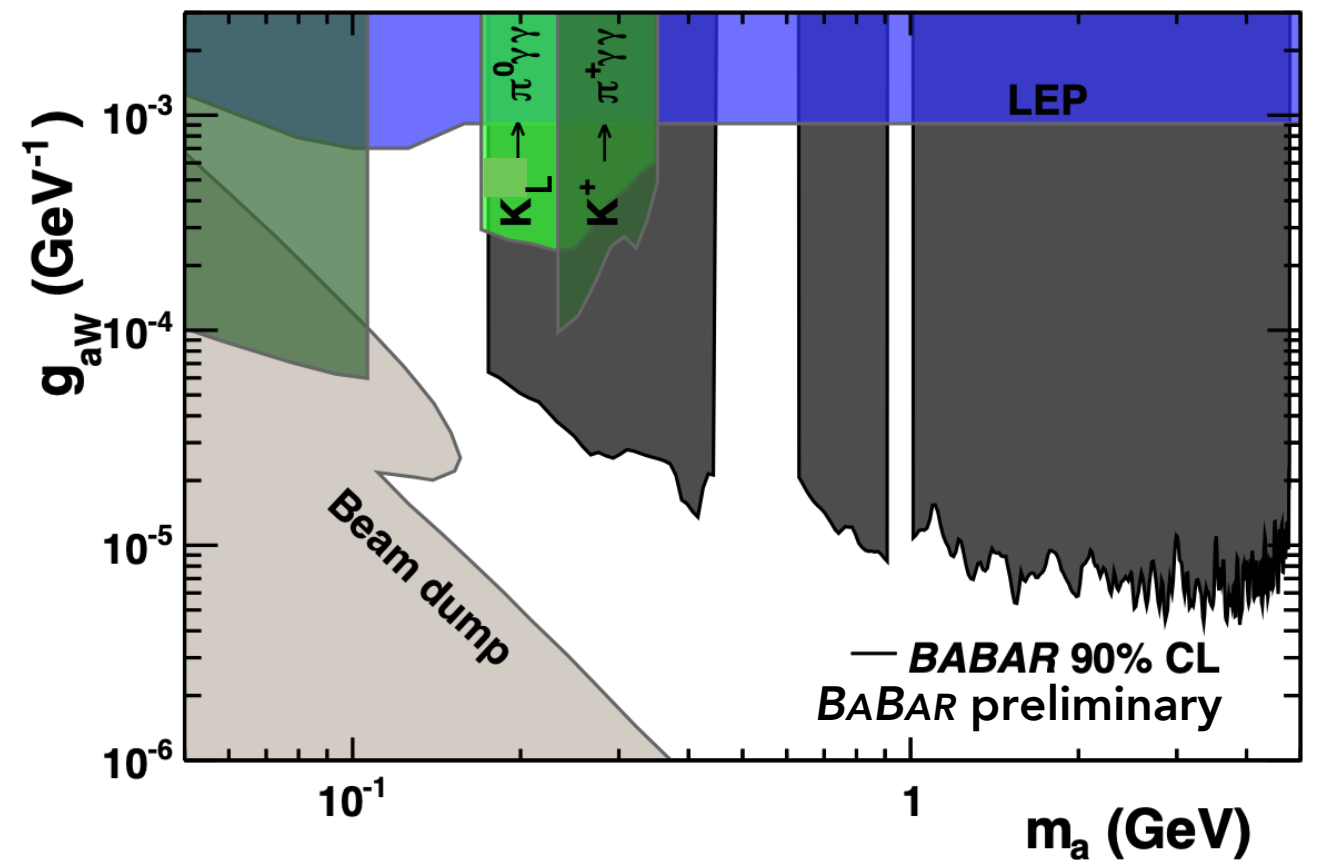
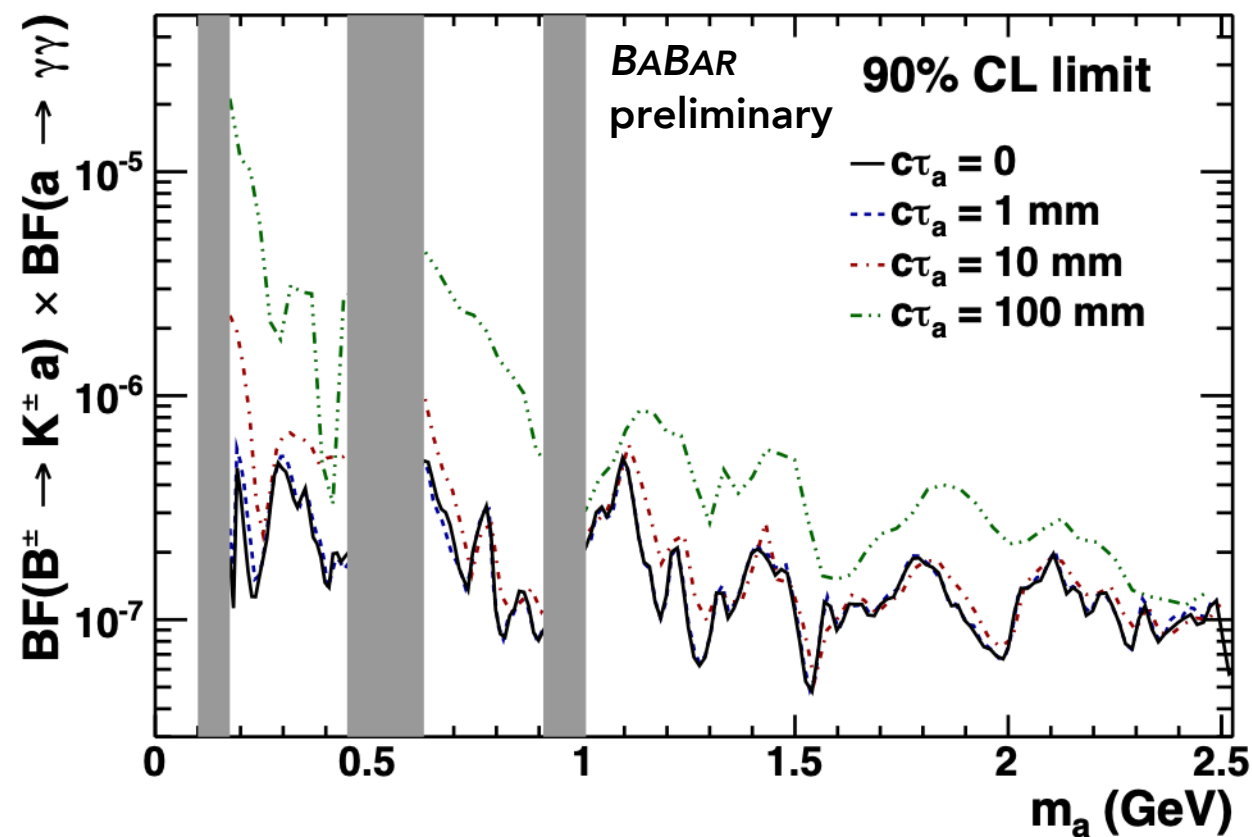


- At longer lifetimes, misreconstruction of displaced photons leads to reduced sensitivity



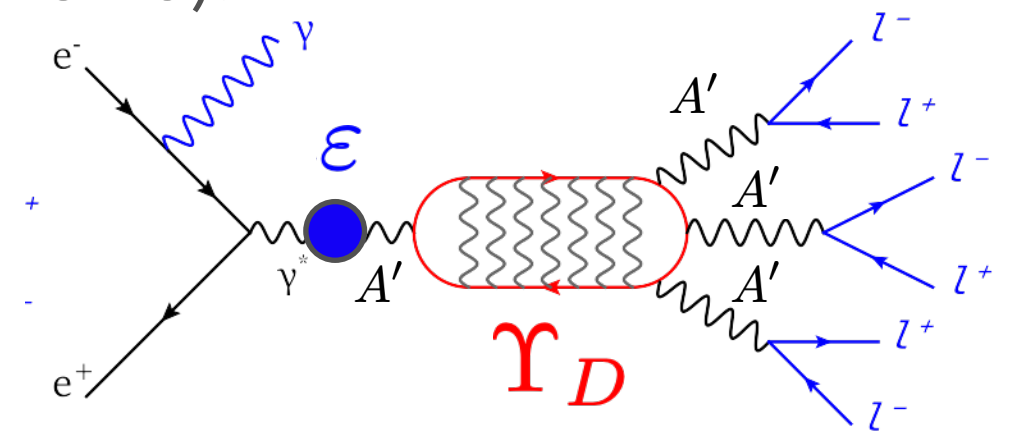
AXIONLIKE PARTICLES

- No significant signal observed; set 90% CL upper limits on branching fraction & ALP coupling



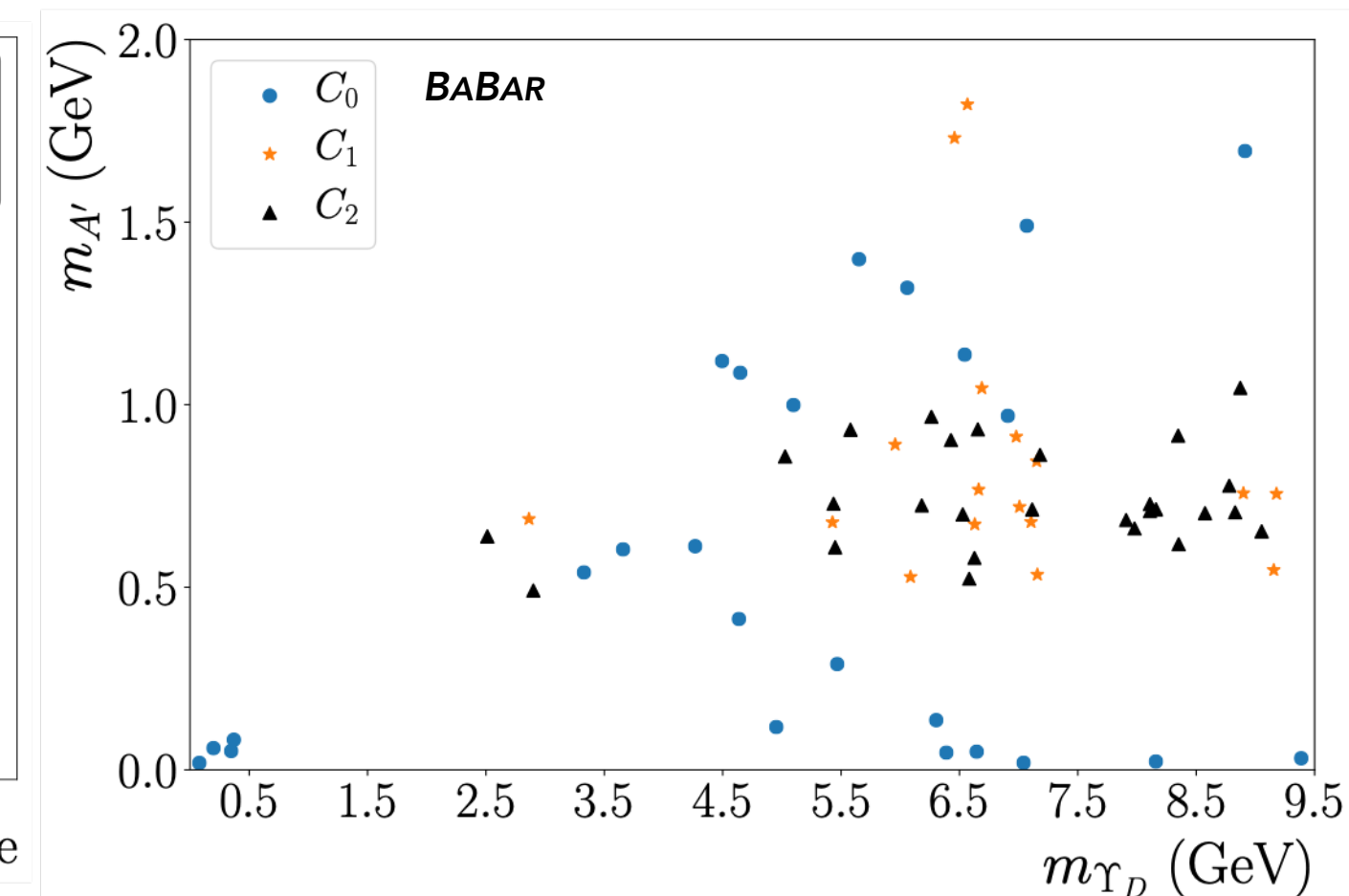
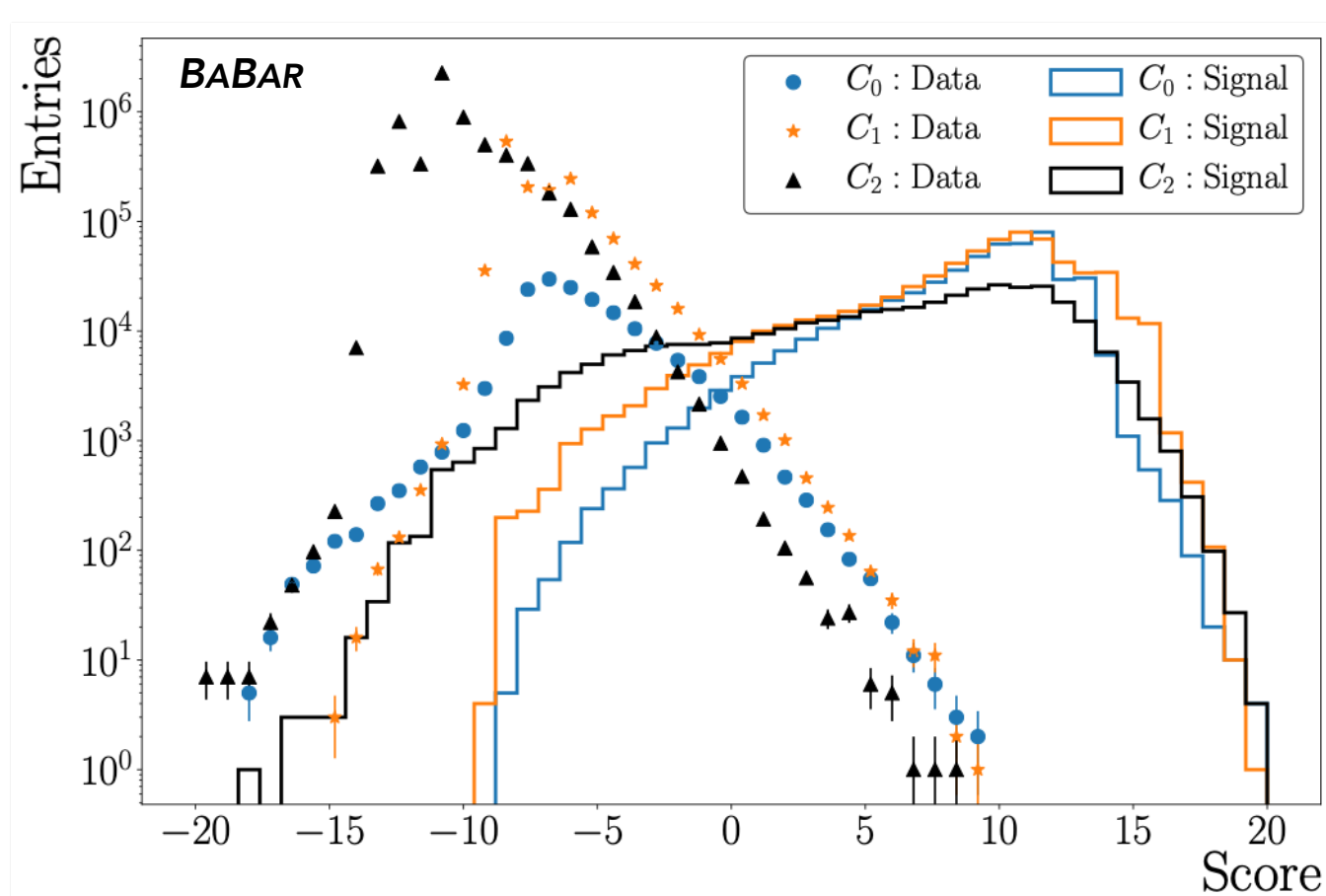
DM BOUND STATE: DARKONIUM

- Consider a DM coupled to dark photon: if coupling in hidden sector is large, can form DM bound states (darkonia)!
- We search for the lightest vector darkonium, Υ_D , which decays into 3 dark photons, A'
- We reconstruct dark photon decays into electron, muon, or pion pairs of similar mass, with at least one lepton pair
- Reconstructed Υ_D must be consistent with recoil off massless photon, should see photon if emitted in detector acceptance
- Train MVAs to further improve signal purity for different final states



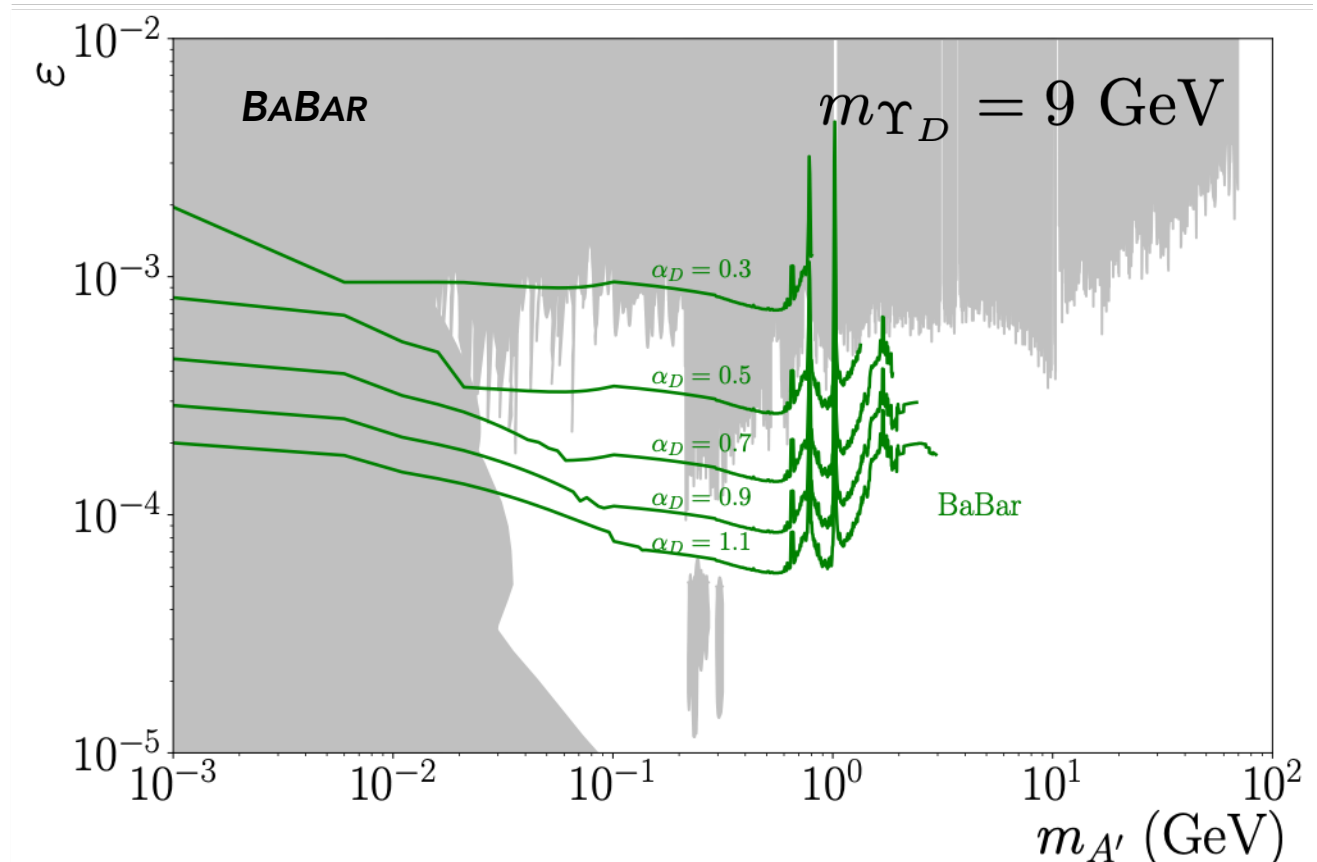
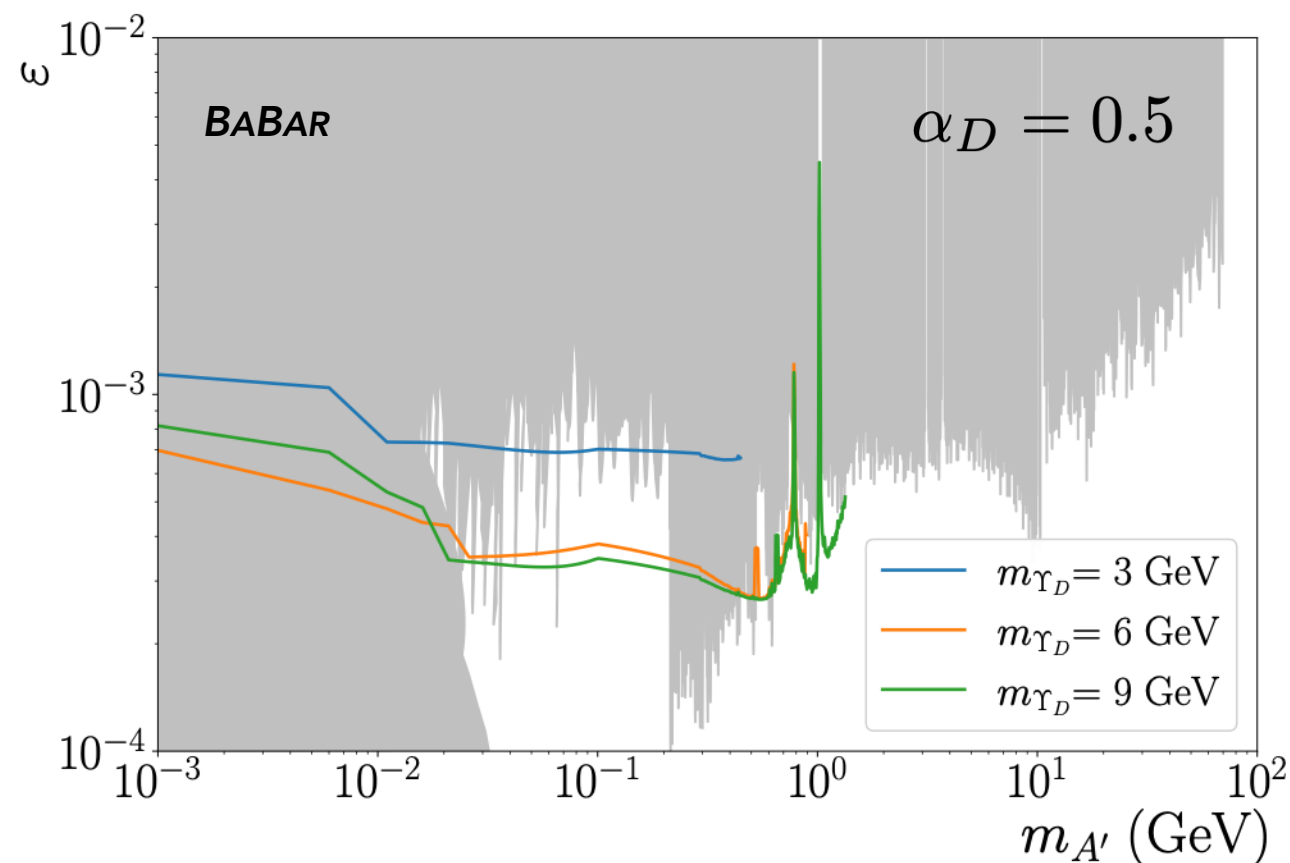
DARKONIUM RESULTS

- C_n sample corresponds to n pion pairs
- Consider window around each mass in the $\Upsilon_D - A'$ plane of width 8x signal resolution, estimate background from adjacent windows



DARKONIUM RESULTS

- Repeat analysis for displaced A' decays, including flight distance and significance in variables used to train MVA
- In absence of significant signal, use profile likelihood method to set 90% CL upper limit on kinetic mixing ε as function of DM coupling



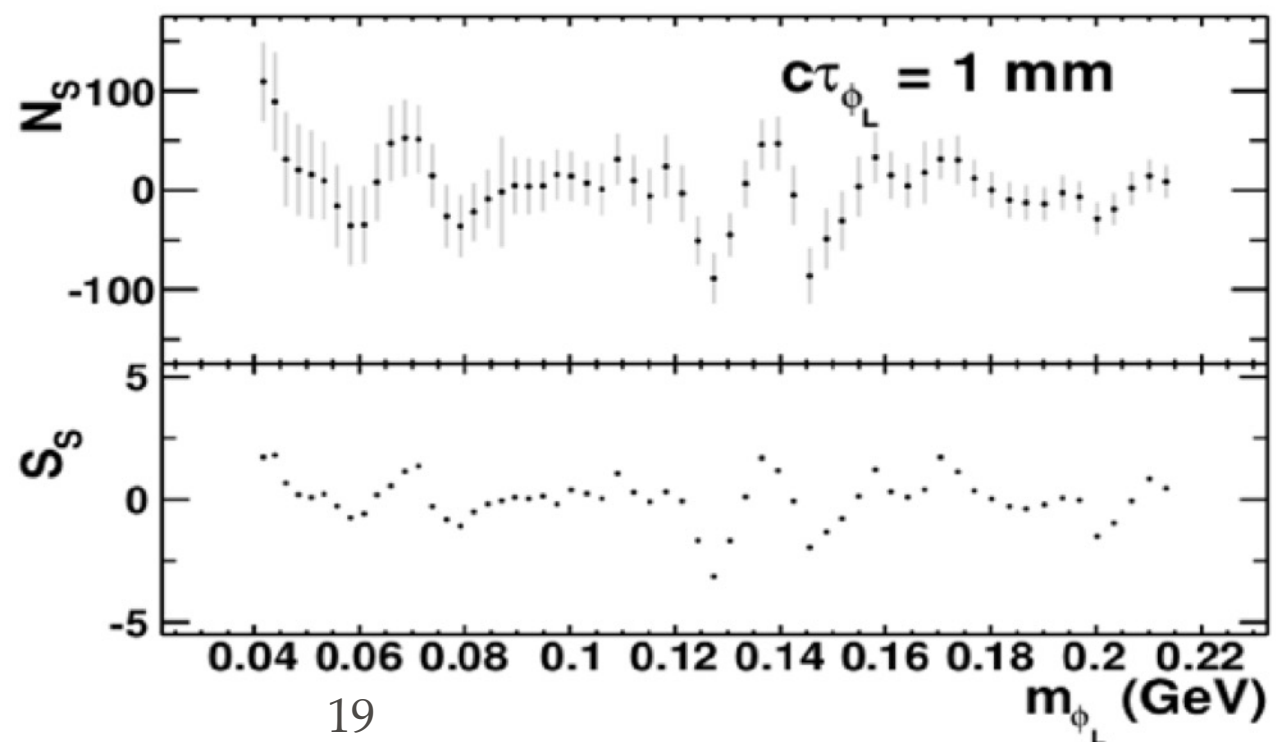
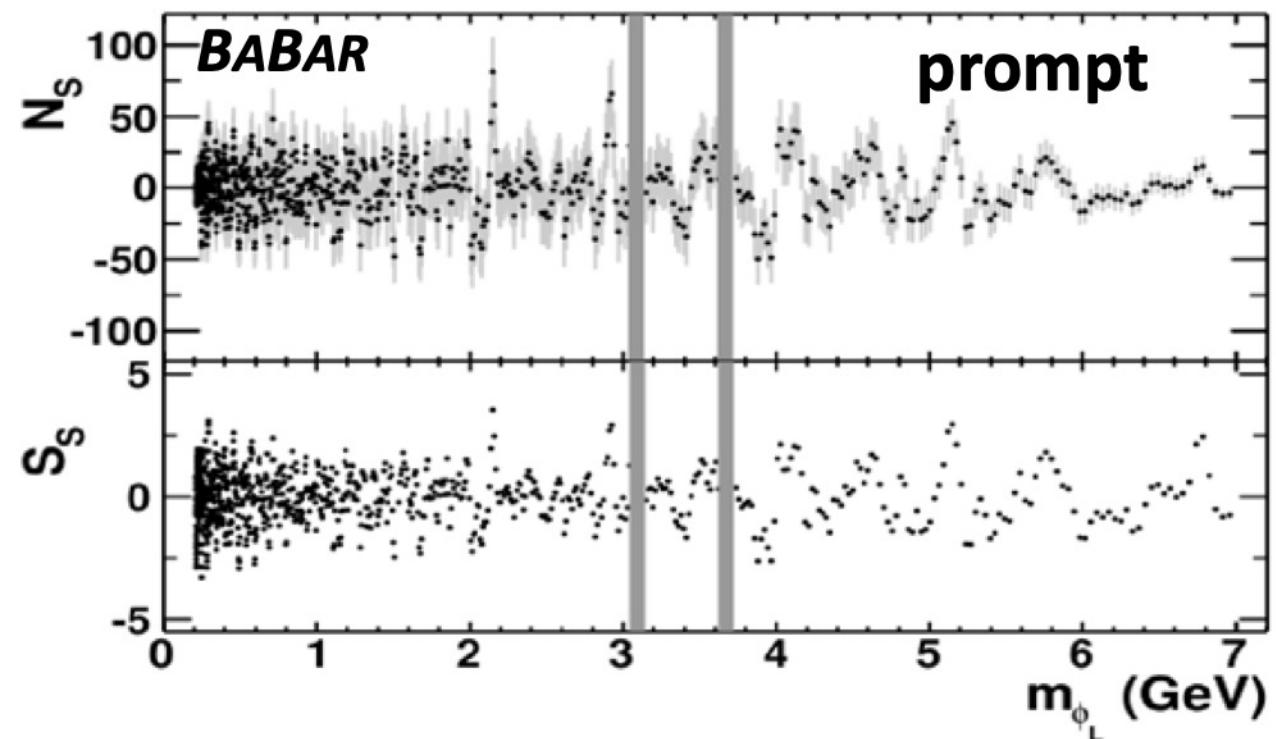
SUMMARY

- B factories are among the best experiments to search for GeV-scale hidden sectors
- Many years after it stopped running, *BABAR* continues to put out new and world-leading hidden-sector results, including recent searches for leptophilic scalars, axionlike particles, and DM bound states
- There are still models that are essentially untested, and new B factory searches can give significant improvement in sensitivity
- Stay tuned for more searches on the way!

BACKUP SLIDES

DARK LEPTOPHILIC SCALAR

- Signal extraction



DARK LEPTOPHILIC SCALAR

- BDT inputs:

TABLE I: List of variables used as input to the dimuon boosted decision trees.

| |
|---|
| Ratio of second to zeroth Fox-Wolfman moment of all tracks and neutrals. |
| Invariant mass of the four track system, assuming the pion (muon) mass for the tracks originating from the tau (ϕ_L) decays. |
| Invariant mass and transverse momentum of all tracks and neutrals. |
| Invariant mass squared of the system recoiling against all tracks and neutrals. |
| Transverse momentum of the system recoiling against all tracks and neutrals. |
| Number of neutral candidates with an energy greater than 50 MeV. |
| Invariant masses of the three track systems formed by the ϕ_L and the remaining positively or negatively charged tracks. |
| Momentum of each track from ϕ_L decays. |
| Angle between the two tracks produced by the tau decay. |
| Variable indicating if a track has been identified as a muon or an electron by PID algorithm for each track. |

TABLE II: List of variables used as input to the dielectron boosted decision trees.

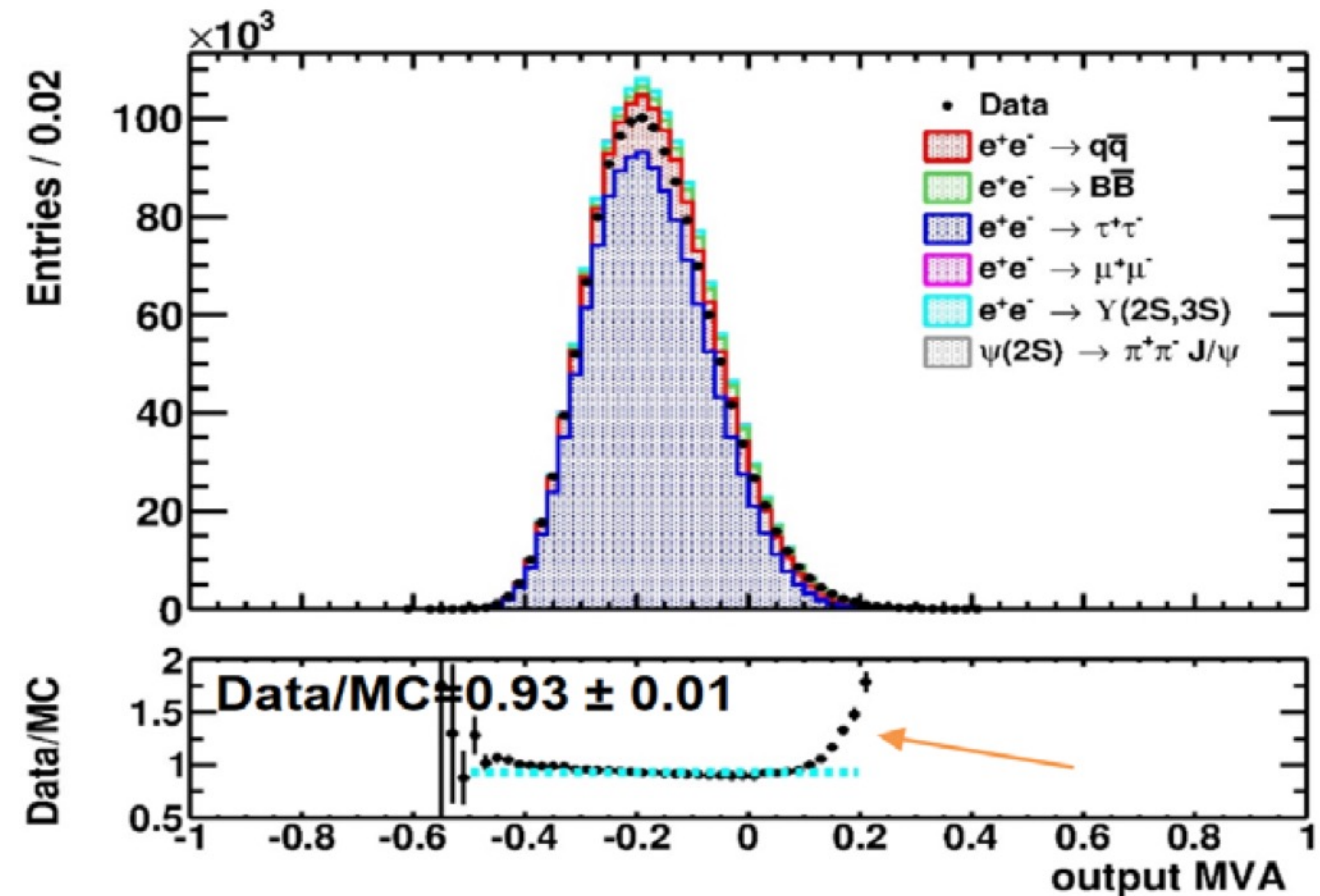
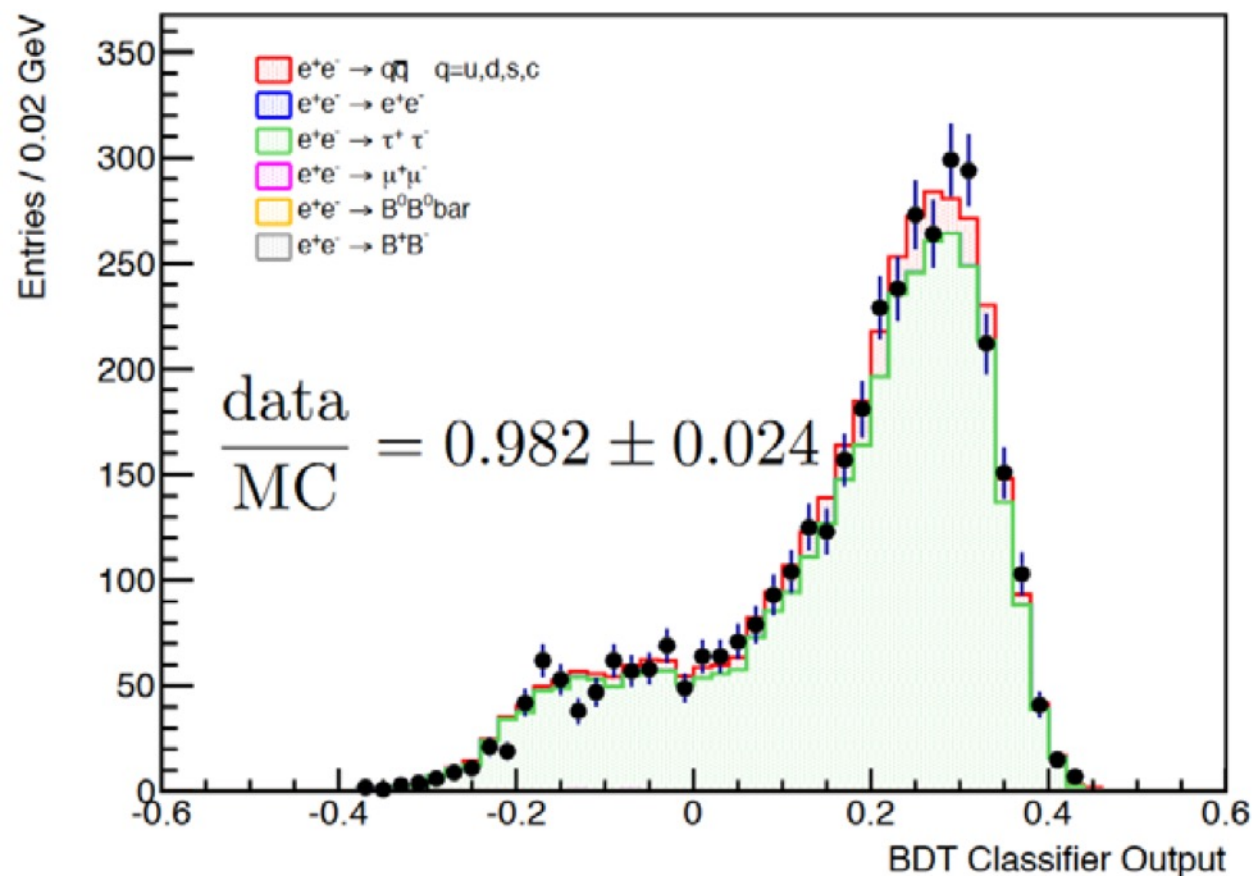
| |
|---|
| Transverse momentum of the system recoiling against all tracks and neutrals. |
| Energy of the system recoiling against all tracks and neutrals. |
| Number of tracks identified as electron candidates by a PID algorithm applied to each track. |
| Angle between ϕ_L candidate momentum and closest track produced in tau decay. |
| Angle between ϕ_L candidate momentum and farthest track produced in tau decay. |
| Angle of ϕ_L candidate relative to the beam in the center-of-mass frame. |
| Angle between the two tracks produced by the tau decay. |
| Angle between ϕ_L candidate and nearest neutral candidate with $E > 50$ MeV. |
| Energy of nearest neutral candidate (with $E > 50$ MeV) to ϕ_L candidate. |
| Total energy in neutral candidates, each of which has an energy greater than 50 MeV. |
| Distance between beamspot and ϕ_L candidate vertex. |
| Uncertainty in the distance between beamspot and ϕ_L candidate decay vertex. |
| ϕ_L candidate vertex significance, defined by the beamspot-vertex distance divided by its uncertainty. |
| Angle between the ϕ_L candidate momentum, and line from beamspot to ϕ_L decay vertex. |
| Distance of closest approach to beamspot of e^- in ϕ_L candidate. |
| Distance of closest approach to beamspot of e^+ in ϕ_L candidate. |
| Transverse distance between ϕ_L decay vertex and best-fit common origin of τ candidates and ϕ_L candidate. |
| χ^2 of the kinematic fit to the ϕ_L and τ candidates constraining their origin to the same production point. |
| χ^2 of the kinematic fit of the ϕ_L candidate with the constraint that the e^+e^- pair is produced from a photon conversion in detector material. |
| Dielectron mass for ϕ_L candidate when re-fit with the photon conversion constraint. |

DARK LEPTOPHILIC SCALAR

- Signal efficiency validation & correction:

$$\tau^- \rightarrow \pi^- \nu_\tau K_S, K_S \rightarrow \pi^+ \pi^-$$

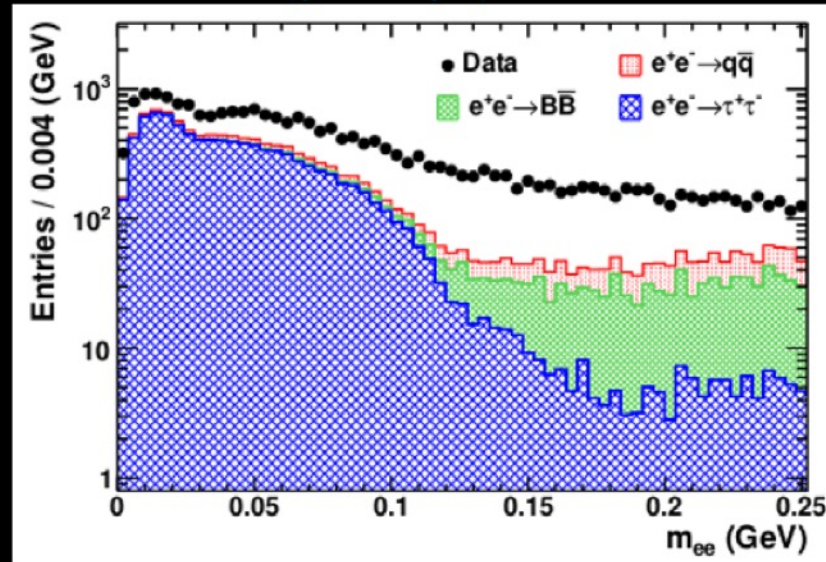
$$p_T^{\text{recoil}} > 2 \text{ GeV}$$



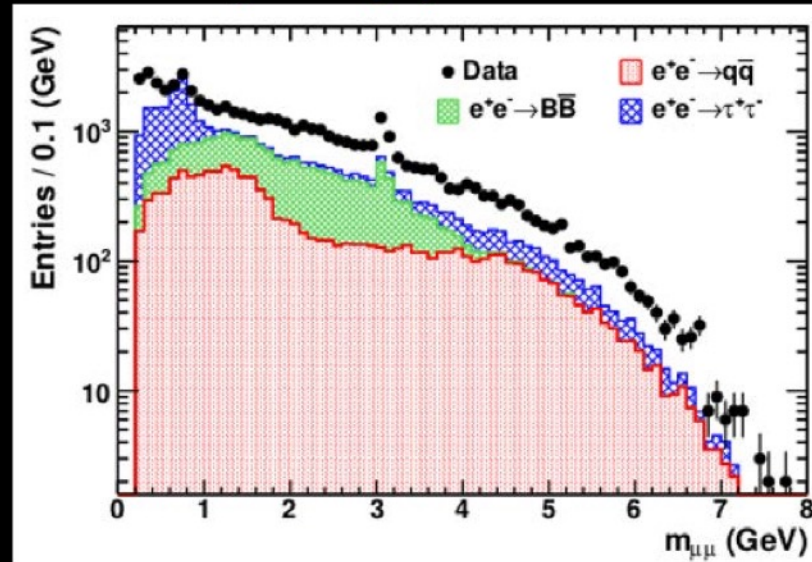
DARK LEPTOPHILIC SCALAR

- Invariant mass distributions:

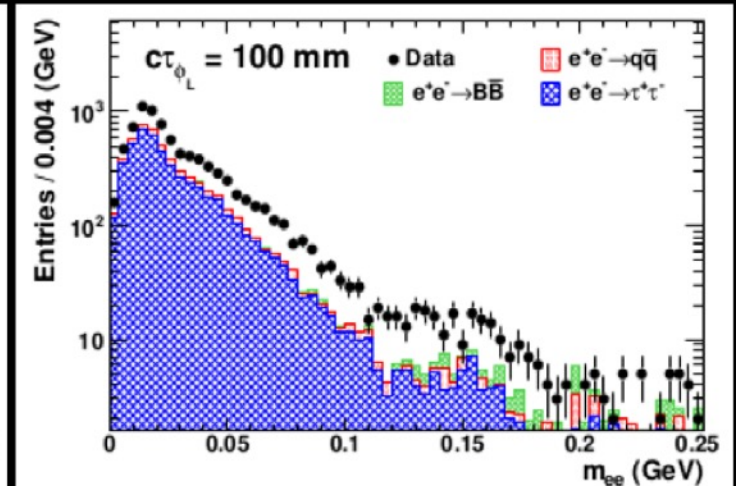
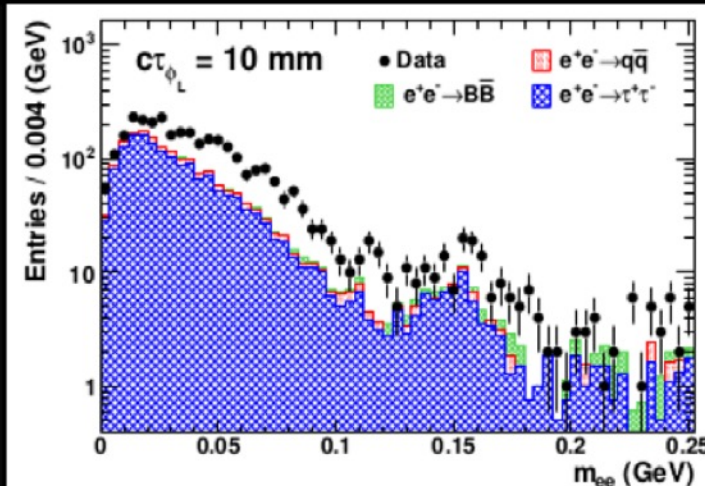
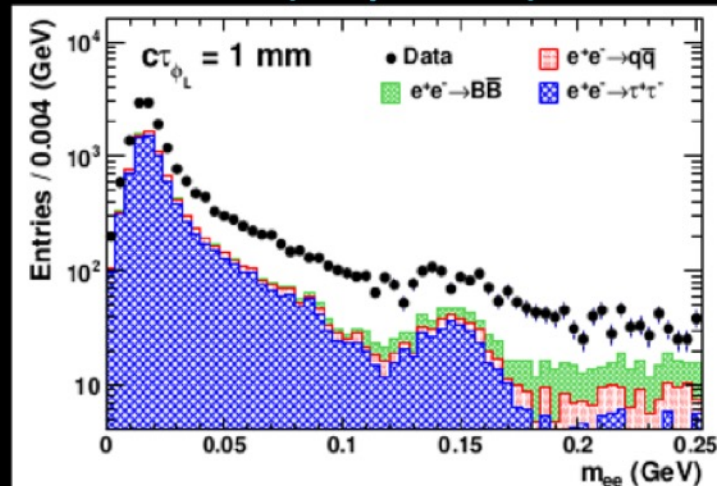
Dielectron (prompt)



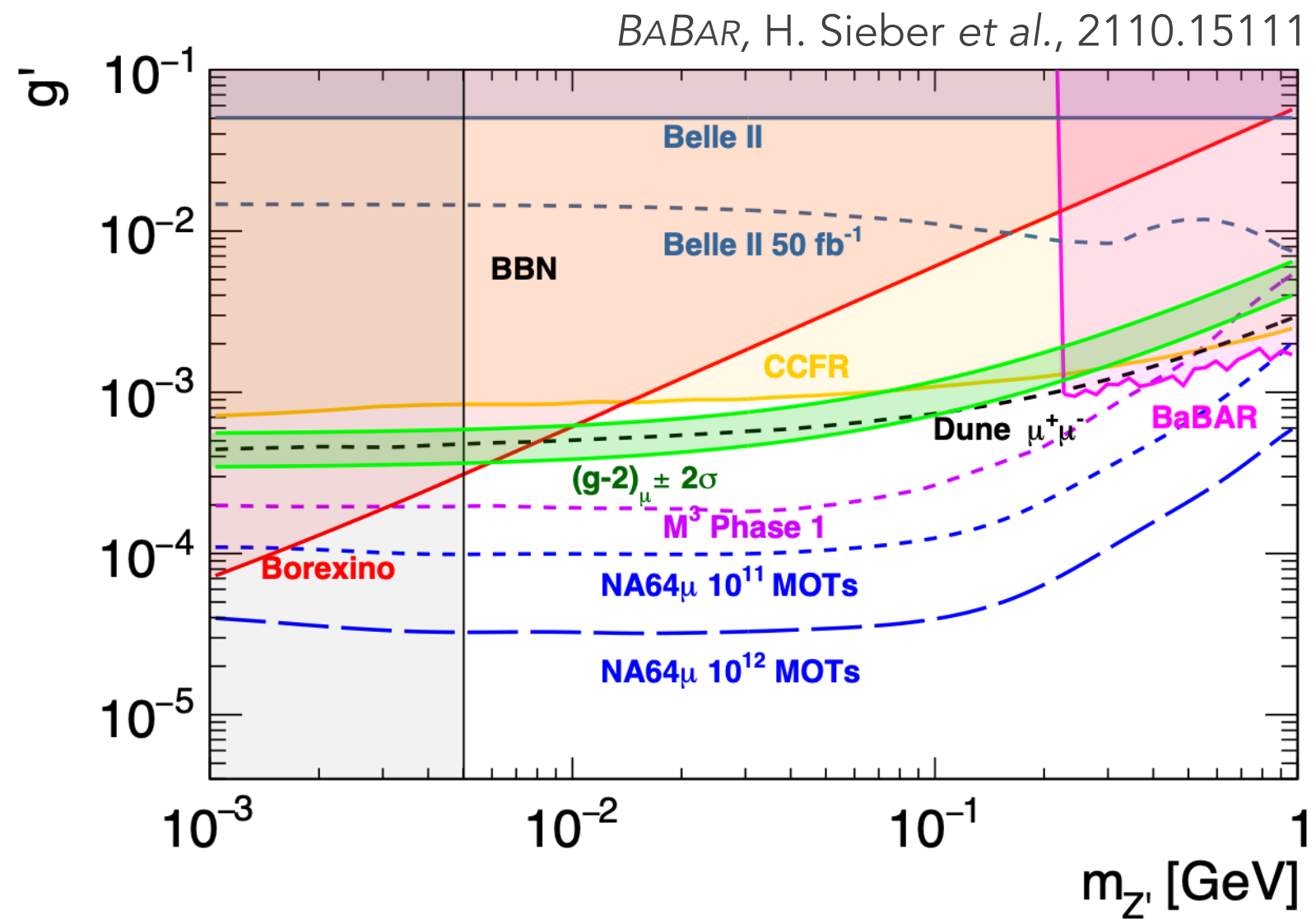
Dimuon (prompt)



Dielectron (displaced)



NA64-MU



ALP SELECTIONS

- **Preselection:** Reconstruct B^\pm candidates from K^\pm candidate and two photons

- Require
$$m_{\text{ES}} = \sqrt{\frac{(s/2 + \vec{p}_i \cdot \vec{p}_B)^2}{E_i^2}} - p_B^2 > 5.0 \text{ GeV}$$

$$|\Delta E| = |\sqrt{s}/2 - E_B^{\text{CM}}| < 0.3 \text{ GeV}$$

- Perform kinematic fit requiring photon and kaon to originate from beamspot, constrain mass to m_{B^\pm} and energy to beam energy
- **Train 2 Boosted Decision Trees:** each is trained on MC for one of the two predominant backgrounds:
 - $e^+e^- \rightarrow q\bar{q} \ (q = u, d, s, c)$
 - $\gamma\gamma e^+e^- \rightarrow B^+B^-$

ALP SELECTIONS

- 13 BDT training observables:

- m_{ES}
- ΔE
- cosine of angle between sphericity axes of B^\pm candidate and rest of event (ROE)
- PID info for kaon candidate
- 2nd Legendre moment of ROE, calculated relative to B^\pm thrust axis
- helicity angle of most energetic photon, and of kaon
- energy of most energetic photon in a candidate
- invariant mass of ROE
- multiplicity of neutral clusters
- invariant mass of diphoton pair, with 1 photon in B^\pm candidate and 1 photon in ROE, closest to each of π^0, η, η'

ALP SIGNAL EXTRACTION

- Perform unbinned maximum likelihood fits for signal peak over smooth background
- 476 mass hypotheses, step size between adjacent mass hypotheses is given by the signal resolution, σ
- σ is determined by fitting a double-sided Crystal Ball function to signal MC at various masses, interpolating for intermediate values
- Resolution ranges from 8 MeV at $m_a = 0.175$ GeV to 14 MeV at $m_a = 2$ GeV, decreasing back to 2 MeV at $m_a = 4.78$ GeV as a result of the kinematic fit
- Signal MC resolution is validated by data/MC comparisons of $B^\pm \rightarrow K^\pm \pi^0$ and $B^\pm \rightarrow K^\pm \eta$, found to be consistent within 3%
- Signal efficiency derived from MC, ranges from 2% at $m_a = 4.78$ GeV to 33% at $m_a = 2$ GeV

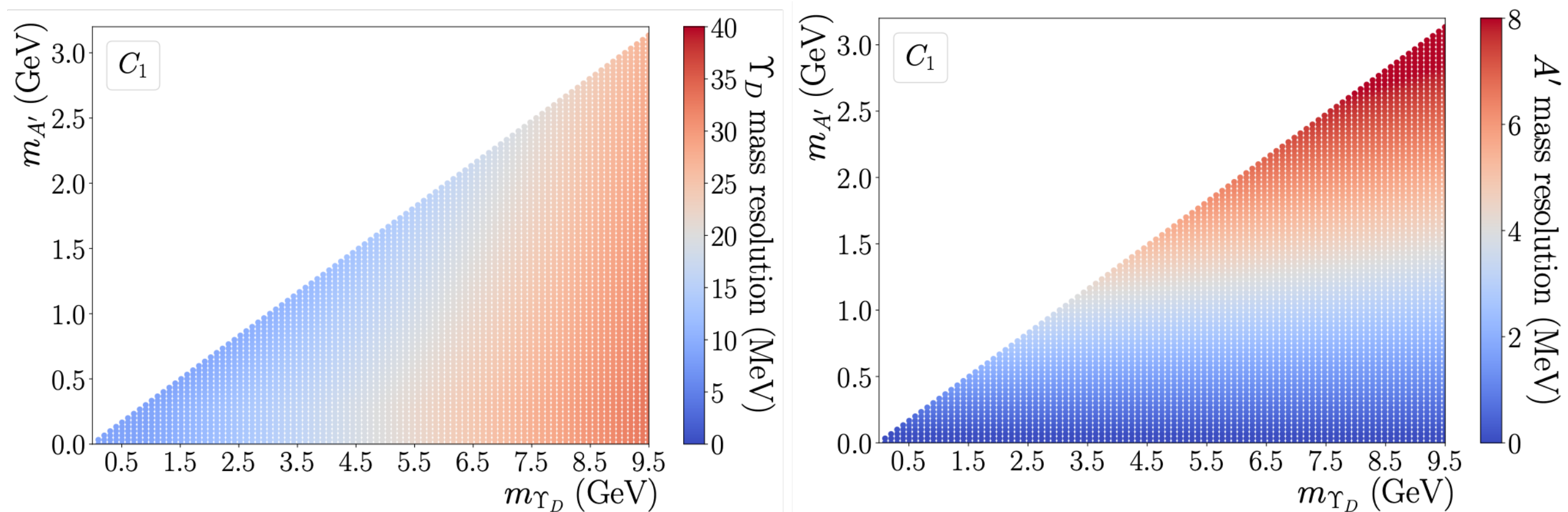
ALP FIT PROPERTIES

- Fits are performed over intervals of length $(30 - 70)\sigma$ depending on ALP mass, restricted to the range $0.11 \text{ GeV} < m_a < 4.8 \text{ GeV}$
- Likelihood function includes contributions from signal, continuum background, peaking background
- **Signal PDF:** modeled from signal MC and interpolated between simulated mass points
- **Continuum background PDF:** second-order polynomial for $m_a < 1.35 \text{ GeV}$, first-order polynomial at higher masses
- **Peaking background PDF:** each SM diphoton resonance is modeled as a sum of a signal template and a broader Gaussian distribution with parameters fixed to fits in MC — this component arises from continuum production of $\pi^0/\eta/\eta'$ that is broadened because of kinematic fit

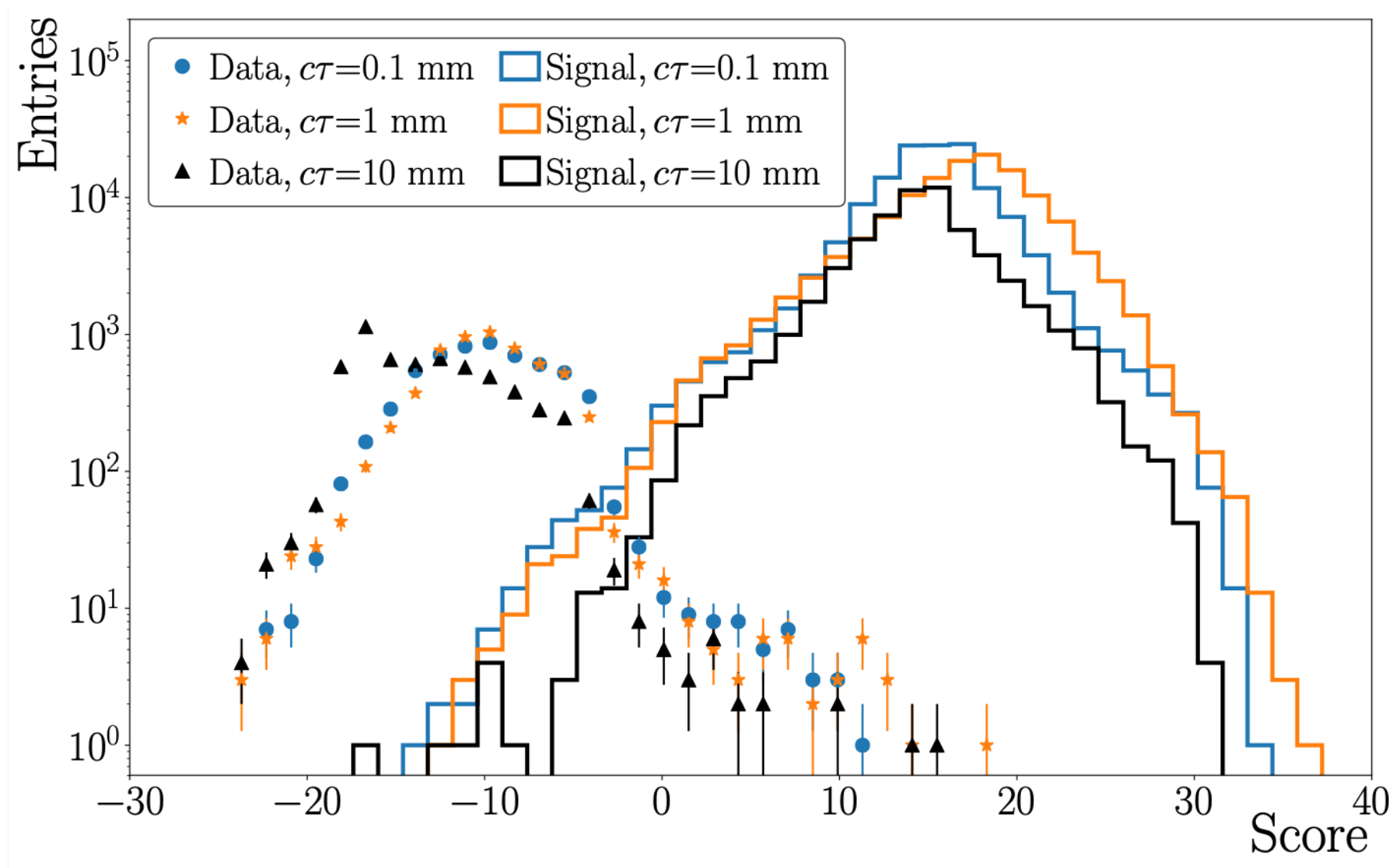
ALP SYSTEMATICS

- Assess uncertainty on signal yield from fit by varying order of polynomial for continuum background (3rd-order for $m_a < 1.35$ GeV, constant at higher mass), varying shape of peaking background within uncertainties, and using next-nearest neighbor for interpolating signal shape
 - Dominates total uncertainty for some masses in vicinity of π^0/η
- Systematic uncertainty on signal yield from varying signal shape width within uncertainty is on average 3% of statistical uncertainty
- 6% systematic uncertainty on signal efficiency, derived from data/MC ratio in vicinity of η'
- Other systematic effects negligible by comparison, including on limited signal MC statistics, luminosity

DARKONIUM: RESOLUTION



DARKONIUM: LONG-LIVED A'



DARKONIUM: LONG-LIVED A'

